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Influence of Nutrient Management Practices on Growth and Yield Performance of Foxtail Millet (*Setaria italica* L.) in Irrigated Conditions

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ABSTRACT

Background: Foxtail millet (*Setaria italica* L.), ancient nutri-cereal rich in calcium, iron and other micronutrients, plays a vital role in food and nutritional security across semi-arid regions. Despite its resilience, productivity in India remains limited due to nutrient deficiencies, reliance on low-yielding varieties and imbalanced fertilizer use.

Methods: The field experiment was conducted during summer (Febraury - April) 2024 at SRM College of Agricultural Sciences, Chengalpattu, Tamil Nadu, to study the influence of integrated nutrient management practices and micronutrient supplementation on growth, yield attributes and productivity of foxtail millet (var. ATL 1). The study was laid out in a split-plot design with three main plot treatments M_1: 100% recommended dose of fertilizer (RDF), M_2: 50% RDF and M_3: Farmyard manure (FYM @ 12.5 t/ha) and four subplot treatments comprising S_1: soil application of TNAU micronutrient mixture (12.5 kg/ha), S_2: foliar spray of $FeSO_4$ (0.5%) + $ZnSO_4$ (0.5%) + Borax (0.2%), S_3: Panchagavya (3%) and S_4: Jeevamrutham (3%). Foliar applications were given at active tillering (30 DAS) and flowering (45 DAS).

Result: The present study revealed that the combined application of 100% RDF with foliar spraying of Fe, Zn and B (M_1S_2) significantly improved plant height, tiller number, dry matter production and yield parameters compared to reduced fertilizer or organic inputs alone. This treatment recorded the maximum number of panicles per hill, grains per panicle, panicle length, panicle weight, grain yield (2486 kg/ha) and straw yield (4571 kg/ha), with a harvest index of 0.47. The improvement was attributed to enhanced nutrient uptake, photosynthetic efficiency and balanced source-sink translocation. The findings highlight that integration of NPK fertilizers with foliar application of Fe, Zn and B is a promising strategy for enhancing yield and resource-use efficiency in foxtail millet cultivation under irrigated conditions.

Key words: Foliar application, Foxtail millet, Integrated nutrient management, Micronutrients, Yield attributes.

INTRODUCTION

Millets, recognized as important nutri-cereals, are cultivated extensively across both local and global scales (Yin *et al*., 2023). They are particularly rich in key micronutrients such as calcium, magnesium, potassium and iron. Remarkably, the calcium content in millets is nearly ten times higher, while the iron concentration is two to ten times greater than that of wheat and rice (Ananthi and Parasuraman, 2020). Foxtail millet, a predominantly self-pollinated species belonging to the Poaceae family, has been cultivated for millennia. It continues to serve as a critical dietary staple for millions of people living in arid and semi-arid regions, highlighting its enduring significance in global agriculture (Sivakumar *et al*., 2022).

In India, small millets occupy around 4.59 lakh hectares, yielding approximately 3.3 lakh tons with an average productivity of 809 kg/ha. However, productivity is often constrained by nutrient and moisture stresses (Louhar *et al*., 2020). Soil fertility, in particular, remains a major limiting factor for crop growth. The potential yield of foxtail millet in India is frequently decreased due to limited fertilizer application, reliance on traditional low-yielding cultivars and inappropriate management practices. Moreover, the adoption of high-yielding varieties in several crops has intensified the use of chemical fertilizers devoid of micronutrients (Murugesan *et al*., 2024). At the same time, the scarcity of organic manures has further aggravated nutrient imbalances and micronutrient deficiencies, ultimately lowering yields. Thus, ensuring

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balanced and adequate supply of both macro and micronutrients is essential for improving crop productivity. Although required in small amounts, micronutrients play indispensable roles in regulating plant growth and development. Among modern techniques, foliar application of micronutrients in liquid form directly to leaves has gained attention. Studies indicate that foliar application can be equally or more effective than soil-based application (Manjunath and Debbarma, 2023). Iron (Fe) is vital for chlorophyll biosynthesis as well as enzymatic and metabolic processes critical to plant survival. Zinc (Zn) supports photosynthesis, nitrogen assimilation, auxin regulation, enzyme activation and ion transport (Wang *et al.*, 2023). Boron (B), another essential element, contributes to cell wall integrity, cell division, reproductive development, sugar transport and hormonal regulation.

MATERIALS AND METHODS

The SRM College of Agricultural Sciences in Chengalpattu, Tamil Nadu, India, hosted the field experiment during the summer (Febraury - April), 2024 under irrigated conditions. The experimental site is located at 12.389°N latitude, 79.742°E longitude and an elevation of 66 meters above mean sea level (MSL) in Tamil Nadu. Before the experiment commenced, a soil sample was collected from the top 15 centimeters of the site. The soil was clayey in texture, with a neutral pH of 7.39, low organic matter content (0.39%) and low levels of available N (100.4 kg/ha) and P_2O_5 (10 kg/ha), but a medium level of available K_2O (160 kg/ha). Weather conditions during the growing season are provided in Fig 1. The experiment was designed as a split-plot, with three main plots and four sub-plots, each replicated three times. The main plots includes M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF and M_3: 12.5 t/ha FYM and Subplot consists of S_1: Soil application of TNAU MN mixture at 12.5 kg/ha, S_2: Foliar spray of 0.5% $FeSO_4$ + 0.5% $ZnSO_4$ + 0.2% Borax, S_3: Foliar spray of 3% Panchagavya and S_4: Foliar spray of 3% Jeevamrutham. The ATL 1 variety foxtail millet seeds was placed 20 × 10 cm apart. Foliar application given at 30 DAS (at active tillering) and 45 DAS (at flowering). At harvest, five randomly selected plants were placed in the net plot area for observations.

Plant height was recorded at harvest by measuring the distance from the base of the stem to the tip of the panicle for five randomly selected plants from each treatment. The number of tillers per hill was observed for the same five plants from each plot and the mean values were calculated. Total dry matter production was also recorded at harvest, where five plants per replication were randomly selected, uprooted, cleaned, sun-dried and then oven-dried at 80°C until reaching a constant weight, expressed as grams per hill.

The number of panicles per hill was determined by counting panicles from five tagged plants and calculating the mean, while grains per panicle were obtained by counting ten panicles and mean was calculated. Panicle length and weight were measured from five randomly selected foxtail millet plants, with length recorded from scar to tip (cm) and weight in grams. Thousand-grain weight was determined by weighing 1000 number of grains sampled from panicles. At full maturity, the crop was harvested, sun-dried, threshed, winnowed and cleaned to record grain yield (kg/ha), while straw yield was separately harvested, dried and expressed in kg/ha. The harvest index was calculated as a percentage using the formula suggested by Donald (1962).

RESULTS AND DISCUSSION

Growth parameters

Among the treatment combination, 100% RDF and 0.5% ferrous sulphate + 0.5% zinc sulphate + 0.2% borax at 30 DAS and 45 DAS (M_1S_2) produced the tallest plant at harvest (Table 1). Plant height showed a 17% increase in treatments receiving 100% RDF combined with foliar application of 0.5% ferrous sulphate + 0.5% zinc sulphate + 0.2% borax, compared to plants supplied with lower NP and 3% jeevamrutham at 30 and 45 DAS. This improvement can be attributed to the foliar supply of micronutrients during the tillering and flowering stages, in conjunction with NPK

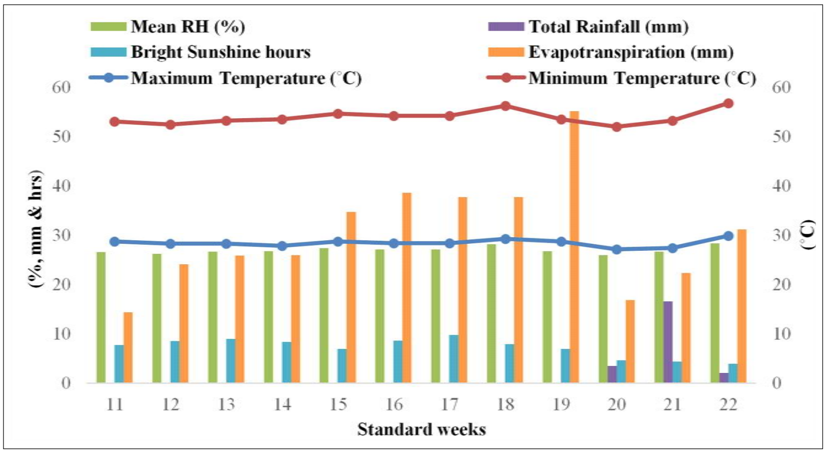


Fig 1: Mean weekly weather parameters during the summer season of the year 2024.

fertilizers, which collectively enhanced plant height. The increase was mainly due to higher photosynthetic efficiency, improved chlorophyll synthesis and the synergistic role of boron in facilitating nitrogen uptake, all of which contributed to vigorous vegetative growth. Similar result was found by John *et al*. (2022) and Manjunath and Debbarma (2023).

Number of tillers per plant

Soil application of 100% RDF along with foliar spray of 0.5% ferrous sulphate + 0.5% zinc sulphate + 0.2% borax at 30 DAS and 45 DAS recorded the higher number of tillers at harvest (Table 1). This improvement may be ascribed to the integrated supply of nutrients through both soil and foliar application. The effect is closely associated with the role of iron as a structural component, essential for photosynthesis and respiration. Elevated levels of NPK, Fe, Zn and B promote the growth and differentiation of axillary buds, leading to increased tiller production. Furthermore, the rapid conversion of assimilated carbohydrates into proteins, along with the enhancement in both number and size of growing cells, contributes to a higher total tiller count per plant. The similar results were reported by Umamaheswari *et al*. (2021) and Yang *et al*. (2023).

Dry matter production

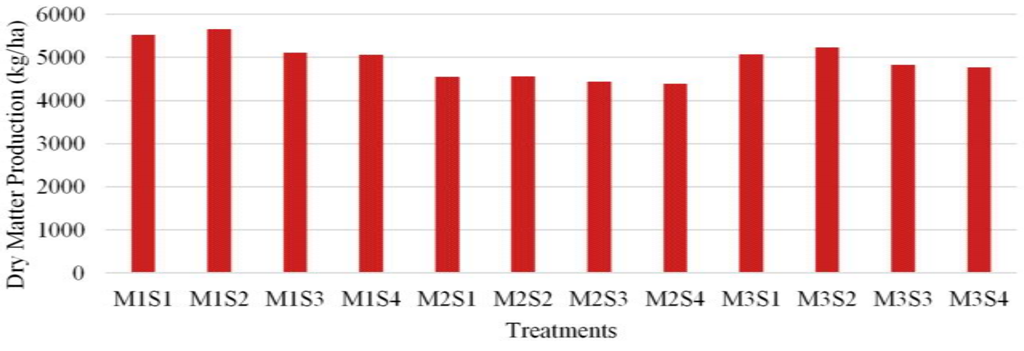
Among the interaction effect, soil application of 100% RDF along with foliar spray of 0.5% ferrous sulphate + 0.5% zinc sulphate + 0.2% borax at 30 DAS and 45 DAS produced the higher DMP at harvest (Fig 2). In foxtail millet, 29 per cent increase in DMP was observed in the plants applied 100 % RDF along with foliar spray of 0.5% ferrous sulphate + 0.5% zinc sulphate + 0.2% borax with compared to plants applied with 50% RDF along with foliar spray of Jeevamrutham.

The combined application of nitrogen and phosphorus along with micronutrients appears to have enhanced crop growth by stimulating dry matter production (DMP). These nutrients influence cellular metabolism, thereby supporting the activity of meristematic tissues and improving nutrient absorption, which ultimately results in greater biomass accumulation (Dass *et al*., 2022). The observed increase in dry matter production may also be associated with the steady and adequate supply of micronutrients throughout

Table 1: Effect of nutrient management practices on plant height and number of tillers/plant of foxtail millet (ATL 1).

	Plant height					Number of tillers/plant			
Treatments	M_1	M_2	M_3	Mean	Treatments	M_1	M_2	M_3	Mean
S_1	95.14	85.67	89.30	90.04	S_1	4.77	2.97	3.91	3.89
S_2	99.47	90.49	94.05	94.67	S_2	5.53	3.11	3.96	4.20
S_3	93.53	85.64	87.36	88.84	S_3	4.37	3.09	3.84	3.77
S_4	92.30	85.34	86.63	88.09	S_4	4.33	2.94	3.68	3.65
Mean	95.11	86.78	89.33		Mean	4.75	3.03	3.85	
	M	S	M × S			M	S	M × S	
SEd ±	4.02	2.90	3.39		SEd ±	0.16	0.12	0.15	
CD (0.05)	8.95	6.45	7.54		CD (0.05)	0.37	0.28	0.33	

Note: Three main plots (M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil application of TNAU micro nutrient mixture 12.5 kg/ha, S_2: Foliar spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham).



The analysis of variance was carried out and comparison was done by Duncan's multiple range test (DMRT) at 5% level of significance [M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil Application of TNAU Micro Nutrient Mixture 12.5 kg/ha, S_2: Foliar Spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham].

Fig 2: Effect of nutrient management on the dry matter production in foxtail millet.

the crop growth period, ensured through foliar application (Zayed *et al*., 2023).

Yield attributes

Number of panicles per hill

The numbers of panicles per hill were shown in Table 2. The panicle number per plant was greatly increased by the application of NPK and micronutrients in foxtail millet. Application of 100% RDF (M_1) recorded the highest value of panicle number (3.65), outperforming M_3 and M_2. Among the subplots, foliar spraying of ferrous sulphate (0.5%) + zinc sulphate (0.5%) + borax (0.2%) registered the highest number of panicle (3.28), which was comparable to S_1 and S_3. In the interaction effect, M_1S_2 registered the higher panicle number (4.03), which was on par with M_1S_1 (3.80). The increase in the number of productive tillers can be ascribed to enhanced dry matter production (DMP) and its effective translocation to grains under adequate nitrogen availability, which in turn improved overall yield attributes. Similar observations in foxtail millet were documented by Sahoo *et al*. (2020). In barnyard millet, Vasundhara and Chhabra (2021) also reported a higher number of productive tillers and improved grain filling, which were attributed to efficient uptake and translocation of macro- and micronutrients applied through foliage at critical growth stages. Comparable results were observed by Abdoli (2020) in barnyard millet.

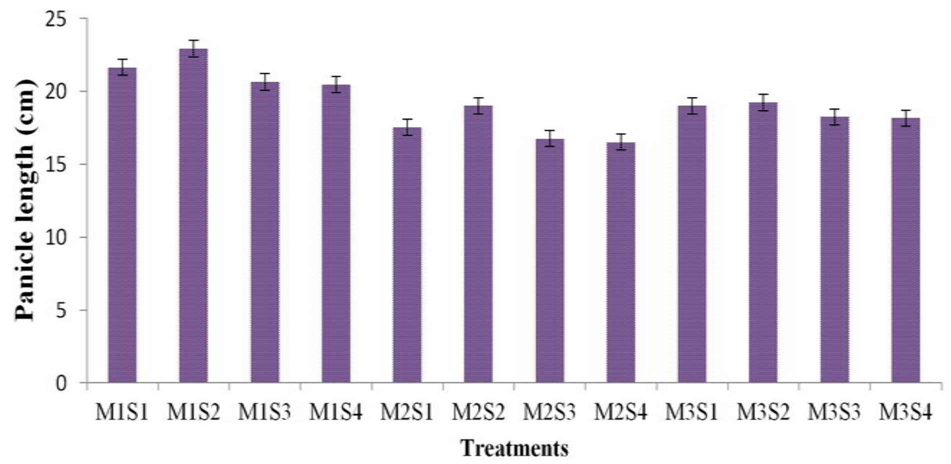
Number of grains per panicle

The combination of both organic and inorganic sources of micro and macro nutrients significantly enhanced the grain numbers in foxtail millet (Table 2). The highest number of grains per panicle (2436) was observed in treatment M_1 (100% RDF), which was significantly different from other treatments. The interaction effect revealed that M_1S_2 (2527) had the highest grains per panicle, comparable to M_1S_1

Table 2: Effect of nutrient management practices on number of panicles per plant and number of grains/ panicle of foxtail millet (ATL 1).

	Number of panicles/plant					Number of grains/panicle			
Treatments	M_1	M_2	M_3	Mean	Treatments	M_1	M_2	M_3	Mean
S_1	3.80	2.50	3.02	3.11	S_1	2452	2047	2189	2229
S_2	4.03	2.62	3.20	3.28	S_2	2527	2109	2277	2304
S_3	3.47	2.40	2.90	2.92	S_3	2386	1993	2143	2174
S_4	3.30	2.12	2.86	2.76	S_4	2378	1956	2135	2156
Mean	3.65	2.41	3.00		Mean	2436	2026	2186	
	M	S	M × S		SEd ±	M	S	M × S	
SEd ±	0.13	0.10	0.11		CD (0.05)	98	54	84	
CD (0.05)	0.29	0.22	0.25			217	119	186	

Note: Three main plots (M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil application of TNAU micro nutrient mixture 12.5 kg/ha, S_2: Foliar spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham).



The analysis of variance was carried out and comparison was done by Duncan's multiple range test (DMRT) at 5% level of significance [M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil Application of TNAU Micro Nutrient Mixture 12.5 kg/ha, S_2: Foliar Spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham].

Fig 3: Effect of nutrient management on the panicle length in foxtail millet.

(2452) and M_1S_3 (2386) in foxtail millet. Boron is a vital micronutrient involved in cell differentiation, pollen grain formation and plant growth. It also facilitates the translocation of photosynthates, thereby enhancing pollination, seed set and overall metabolic activity in plants. Similar results were reported by Kohli *et al*. (2023).

Panicle length and panicle weight

The application of various nutrient sources to the soil and foliar treatments with both micro and macro nutrients registered significant difference in panicle length and weight. The data on panicle length are presented in Fig 3 and panicle weight is presented in Table 3. The interaction effect showed that M_1S_2 had the highest panicle length (22.93 cm), comparable to M_1S_1 (21.65 cm) and M_1S_3 (20.65 cm), while the shortest panicle length in foxtail millet was observed in M_2S_4 (16.52 cm). A similar trend was noted for panicle weight as well. The application of nutrients through foliar spraying at the flowering and grain-filling stages appears to have supported improved nutrient balance, thereby enhancing photosynthetic activity during the post-anthesis phase. This improvement subsequently contributed to better yield traits and overall productivity of foxtail millet, aligning with the observations of Guan *et al*. (2022). For achieving superior yield attributes, micronutrients such as iron, zinc and boron play a crucial role in various enzymatic and physiological processes, including grain development, panicle elongation and weight, dry matter production and chlorophyll synthesis (Karimian *et al*., 2023).

1000-grain weight

The 1000-grain weight values showed no significant differences among the treatments in (Table 3). The interaction effect M_1S_2 (2.60 g) exhibited a higher 1000-grain weight, comparable to M_1S_1 (2.57 g) and M_1S_3 (2.53 g), while the lowest 1000-grain weight was observed in M_2S_4 (2.31 g). This effect can be ascribed to the crucial function of NPK nutrients in supporting meristematic activity and various physiological processes. Their beneficial effect on yield attributes is likely a result of improved nutrient availability, which enhances photosynthate production and facilitates its efficient translocation to the sink (Paul *et al*., 2020).

Grain yield

The grain yield is presented in Table 4. This indicates of foxtail millet was significantly influenced by different levels of macro nutrients and micronutrients. The treatment M_1 (100% RDF) achieved the highest grain yield of 2329 kg/ha, outperforming M_3 (2035 kg/ha) and M_2 (1816 kg/ha). The highest yield in the subplots were registered in the

Table 3: Effect of nutrient management practices on panicle weight and 1000 grain weight of foxtail millet (ATL 1).

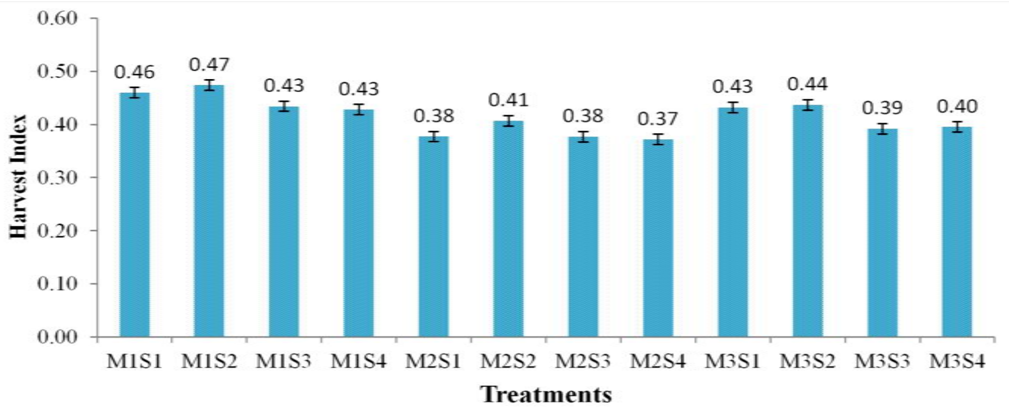
	Panicle weight (g)					1000 grain weight			
Treatments	M_1	M_2	M_3	Mean	Treatments	M_1	M_2	M_3	Mean
S_1	6.83	5.30	6.10	6.08	S_1	2.57	2.33	2.39	2.43
S_2	6.98	5.57	6.19	6.25	S_2	2.60	2.35	2.40	2.45
S_3	6.32	5.12	5.89	5.78	S_3	2.53	2.31	2.37	2.40
S_4	6.22	5.10	5.87	5.73	S_4	2.47	2.31	2.37	2.38
Mean	6.59	5.27	6.01		Mean	2.54	2.33	2.38	
	M	S	M × S		SEd ±	M	S	M × S	
SEd ±	0.20	0.18	0.25		CD (0.05)	0.08	0.07	0.10	
CD (0.05)	0.58	0.42	0.49		0.24	0.17	0.20		

Note: Three main plots (M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil application of TNAU micro nutrient mixture 12.5 kg/ha, S_2: Foliar spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham).

Table 4: Effect of nutrient management practices on grain and straw yield of foxtail millet (ATL 1).

	Grain yield (kg/ha)					Straw yield (kg/ha)			
Treatments	M_1	M_2	M_3	Mean	Treatments	M_1	M_2	M_3	Mean
S_1	2459	1871	2047	2126	S_1	4411	4079	4341	4277
S_2	2486	1848	2148	2161	S_2	4571	4034	4418	4341
S_3	2193	1785	1984	1988	S_3	4189	3662	4083	3978
S_4	2178	1760	1959	1966	S_4	4141	3619	4019	3926
Mean	2329	1816	2035		Mean	4328	3848	4215	
	M	S	M × S		SEd ±	M	S	M × S	
SEd ±	90	66	77		CD (0.05)	139	124	175	
CD (0.05)	201	147	172		406	291	340		

Note: Three main plots (M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil application of TNAU micro nutrient mixture 12.5 kg/ha, S_2: Foliar spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham).



The analysis of variance was carried out and comparison was done by Duncan's multiple range test (DMRT) at 5% level of significance [M_1: 100% RDF (40:20:0 kg/ha), M_2: 50% RDF, M_3: 12.5 t/ha FYM) and four subplots (foliar application, S_1: Soil Application of TNAU Micro Nutrient Mixture 12.5 kg/ha, S_2: Foliar Spray of $FeSO_4$ 0.5% + $ZnSO_4$ 0.5% + Borax 0.2%, S_3: 3% Panchagavya, S_4: 3% Jeevamrutham].

Fig 4: Effect of nutrient management on the Harvest index in foxtail millet.

plants applied with spraying of ferrous sulphate (0.5%) + zinc sulphate (0.5%) + borax (0.2%) through foliage. However, Application of 100 % RDF along with foliar application of ferrous sulphate (0.5%) + zinc sulphate (0.5%) + borax (0.2%) at critical stages showed the highest grain yield at 2486 kg/ha, which was comparable to M_1S_1. The observed increase in grain yield is likely attributed to enhanced metabolic activity and the efficient translocation of carbohydrates from source to the sink. In foxtail millet, higher productivity was achieved through effective nutrient uptake and their subsequent mobilization to developing tillers during critical growth phases. Yield improvement showed a positive association with the availability of NPK throughout the crop growth period, aligning with the findings of Shahzadi *et al*. (2025). Likewise, Swaroop and Debbarma (2023) suggested that improved carbohydrate synthesis and its transport to the grain formation site may explain the yield benefits associated with zinc fertilization.

Furthermore, Sivakumar *et al*. (2022) reported that zinc application enhances plant nutrition and dry matter accumulation, which in turn contributes to increased biological yield.

Straw yield

The data on effect of nutrients on straw yield found to be significantly different (Table 4). Application of 100% RDF resulted in the highest straw yield of 4328 kg/ha, outperforming the other treatments. Similarly, foliar feeding of ferrous sulphate (0.5%) + zinc sulphate (0.5%) + borax (0.2%) recorded the highest straw yield of 4341 kg/ha, followed by S_1. Among the interaction effect, application of 100 % RDF along with foliar application of ferrous sulphate (0.5%) + zinc sulphate (0.5%) + borax (0.2%) (M_1S_2) at critical stages showed the highest straw yield of 4571 kg/ha, which was significantly different from M_1S_3 (4189 kg/ha) and comparable to M_1S_1 (4411 kg/ha). The application of zinc appears to have contributed to the regulation of essential physiological processes in plants, especially chlorophyll synthesis, which subsequently enhanced straw yield in foxtail millet. This positive effect is associated with improved growth and developmental functions, as documented by John *et al*. (2022) and Yin *et al*. (2023).

Harvest index

The treatment M_1S_2 shown higher HI value of 0.47 and lowest was registered in M_2S_4 (Fig 4). This indicates that the increase in these yield attributing traits would result in higher grain yield through a significant increase in HI. However, increase in HI alone may reduce the biomass investment in leaves and other vegetative structures, loosing total biomass production (Paul *et al*., 2020). Therefore, it is appropriate to focus on ways and means to increase the biomass by maintaining higher HI values in foxtail millet (Sivakumar *et al*., 2022).

CONCLUSION

This study confirmed that integrated nutrient management plays a pivotal role in enhancing growth, yield attributes and productivity of foxtail millet under irrigated conditions. The treatment combining 100% RDF with foliar application of Fe, Zn and B recorded superior performance in plant height, tiller number, leaf area index, dry matter production and yield traits. Enhanced grain and straw yields were achieved through balanced nutrient supply and improved physiological efficiency. The results underline the importance of integrating macro and micronutrients to overcome yield limitations in millet cultivation. These findings provide a practical approach for sustainable intensification of foxtail millet production. Future studies should validate the effectiveness of nutrient combinations under different soil and climatic conditions while exploring eco-friendly organic supplements for long-term sustainability.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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