



RESEARCH ARTICLE

Micronutrient interventions for enhancing yield and quality of fodder sorghum

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Received: 01 November 2025; Accepted: 25 May 2026; Available online: Version 1.0: 22 July 2026

Cite this article: Patel HK, Rathod PH. Micronutrient interventions for enhancing yield and quality of fodder sorghum. Plant Science Today. 2026; 13(sp5): 1-9. <https://doi.org/10.14719/pst.12535>

Abstract

Deficiency or malnutrition occurs due to the lack of micronutrients, which results from the deficiency of essential micronutrients in the soil. Micronutrient deficiency of zinc (Zn) and iron (Fe) in grains, as well as in feed and fodder, create a serious issue globally. The dairy industry is highly dependent on the availability of high-quality fodder for cattle feeding. Agronomical biofortification is a simple and effective way to correct micronutrient deficiencies. Green biomass and fodder quality are important aspects of feed and fodder. To achieve these objectives, an experiment was conducted at the Main Forage Research Station, Anand Agricultural University, Anand (Gujarat) during kharif 2019 and 2020. Green fodder yield, dry matter yield and crude protein yield are major parameters of quality fodder. The treatments consisted of soil application of Zn and Fe as basal applications followed by foliar application of Zn and Fe at 30 and 45 days after sowing (DAS). After two years of experimentation on Zn and Fe micronutrients on sorghum fodder in the semi-arid region of Gujarat (India). The results revealed that an application of 20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray reported significantly higher green fodder yield (826.39 % and 575.00 %), dry matter yield (273.8 and 196.08 q/ha) and crude protein yield (12.83 and 12.21 q/ha) in season I and season II respectively. The experiment conducted indicated that agronomical biofortification in fodder sorghum improved the Zn and Fe content as well as their uptake by the crop, thereby enhancing the quality of fodder sorghum compared to no application of Zn and Fe. It is an effective supplementation strategy to overcome Zn and Fe deficiency in fodder crops.

Keywords: biofortification; crude protein; crude protein yield; dry matter; dry matter yield; fodder sorghum; green fodder yield; iron; zinc

Introduction

India is fortunate to possess a rich and diversified livestock population (1). The integration of agriculture and animal husbandry has been an integral part of Indian society since ancient times and is deeply rooted in cultural, religious and economic traditions (2). This bond continues today, with agriculture and animal husbandry functioning as interrelated sectors that are often described as two sides of the same coin. Their relationship remains crucial not only from an economic perspective but also in social and cultural aspects across rural India (3).

Mixed farming systems, which incorporate both crop production and livestock rearing, play a vital role in sustaining rural livelihoods and ensuring food and nutritional security (2, 4). Although India accounts for only 2.29 % of the world's land area, it supports approximately 17.4 % of the global human population and 10.7 % of the global livestock population. This creates significant pressure on land, water and other natural resources (5).

Micronutrient deficiencies, particularly of zinc (Zn) and iron (Fe), are a major concern in Indian agriculture, in addition to human health. These deficiencies, often referred to as "hidden hunger" or malnutrition, affect both plant and animal productivity as well as human health (5). They are more commonly observed in Indo

Gangetic plains, Gujarat, Maharashtra, Karnataka, etc. The widespread occurrence of micronutrient deficiencies has been reported from various regions in India.

To address these challenges, agronomic interventions such as micronutrient fortification through soil and foliar application, breeding strategies and the development of fortified fodder varieties have been recommended (6). Agronomic biofortification is an effective approach to enhance the concentration of essential micronutrients such as Zn and Fe in crops through the application of fertilisers and improved crop management practices. It helps improve crop productivity, nutritional quality and soil fertility. This strategy is economical, practical and useful for reducing hidden hunger in humans and livestock, thereby contributing to better health outcomes for both livestock and humans (7, 8).

Among various essential micronutrients, Zn and Fe have been recognised by the World Health Organization (WHO) as two of the most important factors influencing global malnutrition. These elements are essential for both plants and animals and play critical roles in metabolic and physiological processes (9).

The Zn and Fe are transition metals with unpaired electrons that actively participate in oxidation-reduction (redox) reactions within living organisms (10, 11). According to earlier findings, both

micronutrients are essential for human growth and development. They also play a vital role in the synthesis of chlorophyll and the maintenance of chloroplasts in plants (12).

Zinc is a key micronutrient involved in numerous biochemical and physiological pathways. It is essential for enzyme activation, carbohydrate metabolism, protein synthesis and cell division. Zinc also plays an important role in photosynthesis, nitrogen metabolism and the overall growth and development of plants (13). Enhancing Zn availability in plants contributes to improved yield, nutrient quality and plant resilience.

Iron is equally important, particularly in the synthesis of proteins such as leghemoglobin and nitrogenase, which are vital for nitrogen fixation in legumes. Iron deficiency in plants can severely affect nodule development and overall plant health. In animals, Fe is necessary for the production of hemoglobin and myoglobin and its deficiency leads to anemia especially in young calves (10). According to scientific reports, anemia caused by Fe deficiency remains a widespread problem globally (13, 14).

Green fodder is the major and primary component of livestock feed in India. Its cultivation is more concentrated in areas with a high livestock population and the availability of irrigation facilities and its nutritional quality directly influences animal productivity and health. Agronomic biofortification through soil or foliar application of micronutrients has emerged as an effective strategy to enhance the yield and nutritional quality of fodder crops. In this context, the present study was undertaken to evaluate the effect of Zn and Fe application on the yield and quality of fodder sorghum, with the objective of improving its nutritional value and supporting sustainable livestock production (15, 16).

In this context, the present study was designed with the broader objective of evaluating the effect of micronutrient application, specifically Zn and Fe, on the yield and quality of fodder sorghum. This experiment aims to contribute to sustainable livestock production by improving the nutritional profile of fodder through agronomic biofortification.

Materials and Methods

Experiment site and climate

The two-year field experiment was conducted during kharif 2019 and 2020 at the Main Forage Research Station, ICAR Unit 9, Anand Agricultural University, Anand, Gujarat, India, which is geographically located at 22°35' North latitude and 72°55' East longitude, with an altitude of 45.1 m above mean sea level. Anand

is situated about 70 km from the Arabian Sea coast; therefore, the climate of this location is semi-arid and sub-tropical, with a dry and hot summer. The monsoon season usually begins in the third week of June and ends in the middle of September, with an average annual rainfall of 864.5 mm, most of which is influenced by south-west monsoon currents. July and August are the months of heavy precipitation. The average metrological parameters of selected weather conditions at Anand during June 2019 to August 2019 (cropping season 1) and June 2020 to August 2020 (cropping season 2) were collected from the Department of Agricultural Meteorology, Weather observatory, B.A. College of Agriculture, Anand Agricultural University, Anand (Fig. 1 and 2).

Analysis of soil sample for basic properties

The physico-chemical properties of the soil were determined by following standard analytical procedures (Table 1). Mechanical analysis of the experiment soil was carried out using the International Pipette Method (17). The electrical conductivity (EC) and soil pH were determined using an Elico glass electrode pH meter and solubridge conductivity meter respectively (18). Soil organic carbon was determined by the rapid titration method (19) as described in the reference book (20). The research site had sandy loam in texture and contained available nitrogen (232.87 kg/ha), available phosphorus (35.12 kg/ha) and available K₂O (282.20 kg/ha). Available phosphorus and potassium in the soil were determined by Olsen's method (spectrophotometric) and flame photometric method respectively (20, 21).

Experiment design

The experiment was laid out in randomised complete block design (RCBD) with 4 replications and 7 treatments. The details of the treatments are given in Table 2. For the experiment, fodder sorghum variety (GAFS 12, Gujarat Anand Fodder Sorghum 12), recommended for the Gujarat region, was used. The seeds were sown in open rows at a seed rate of 80 kg/ha during the second week of June in both 2019 and 2020. The individual plot size of the experiment was 3.60 × 5.00 m (18 sq m²) with a row spacing of 30 cm, consisted of a total of 12 rows, while the net plot area had 8 rows covering 9.6 sq m². The recommended dose of fertiliser (80-40-0 kg NPK/ha) was applied. A total of 50 % nitrogen (40 kg N/ha) and the full dose of phosphorus (40 kg/ha) were applied through urea and single superphosphate respectively as basal application and the remaining half dose of nitrogen was top-dressed at 30 days after sowing (DAS). According to the predefined micronutrient treatments, ZnSO₄ and FeSO₄ were applied as soil and foliar applications at 30 and 45 DAS. This was followed by pre-

Table 1. Basic physicochemical properties of soil before the sowing of crop

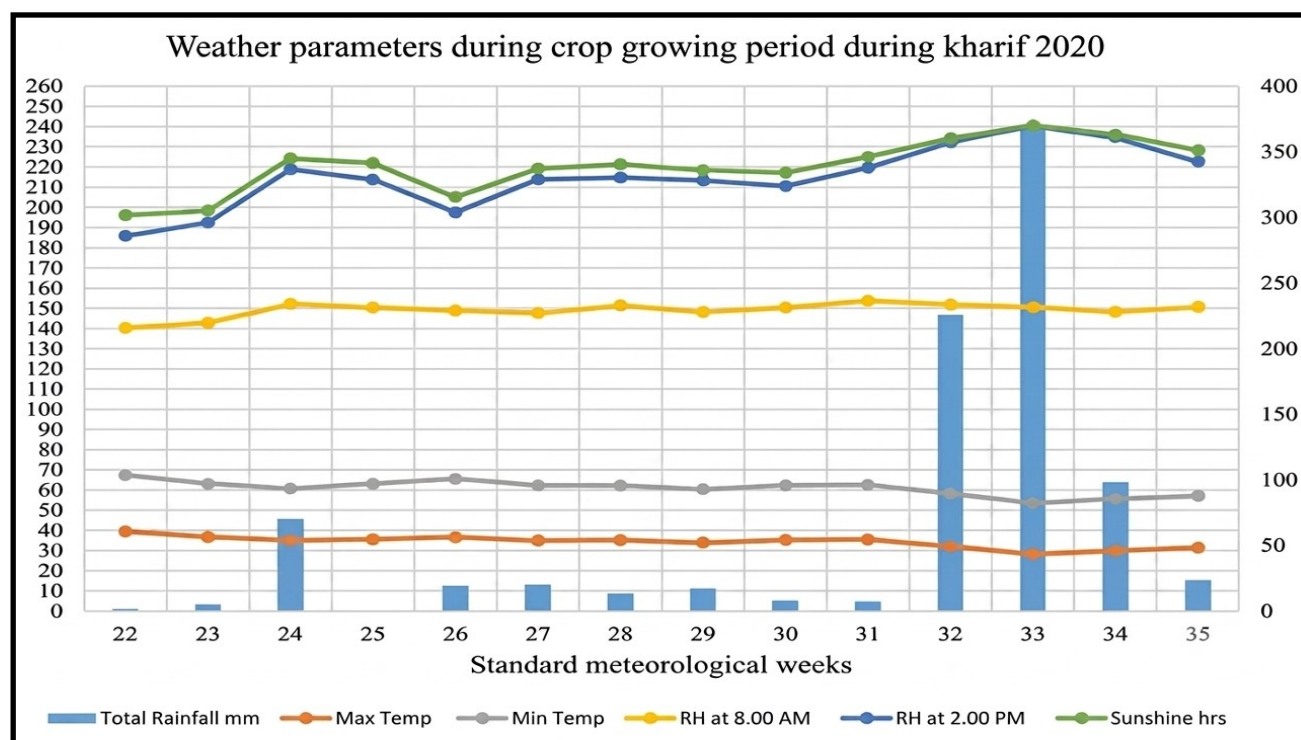
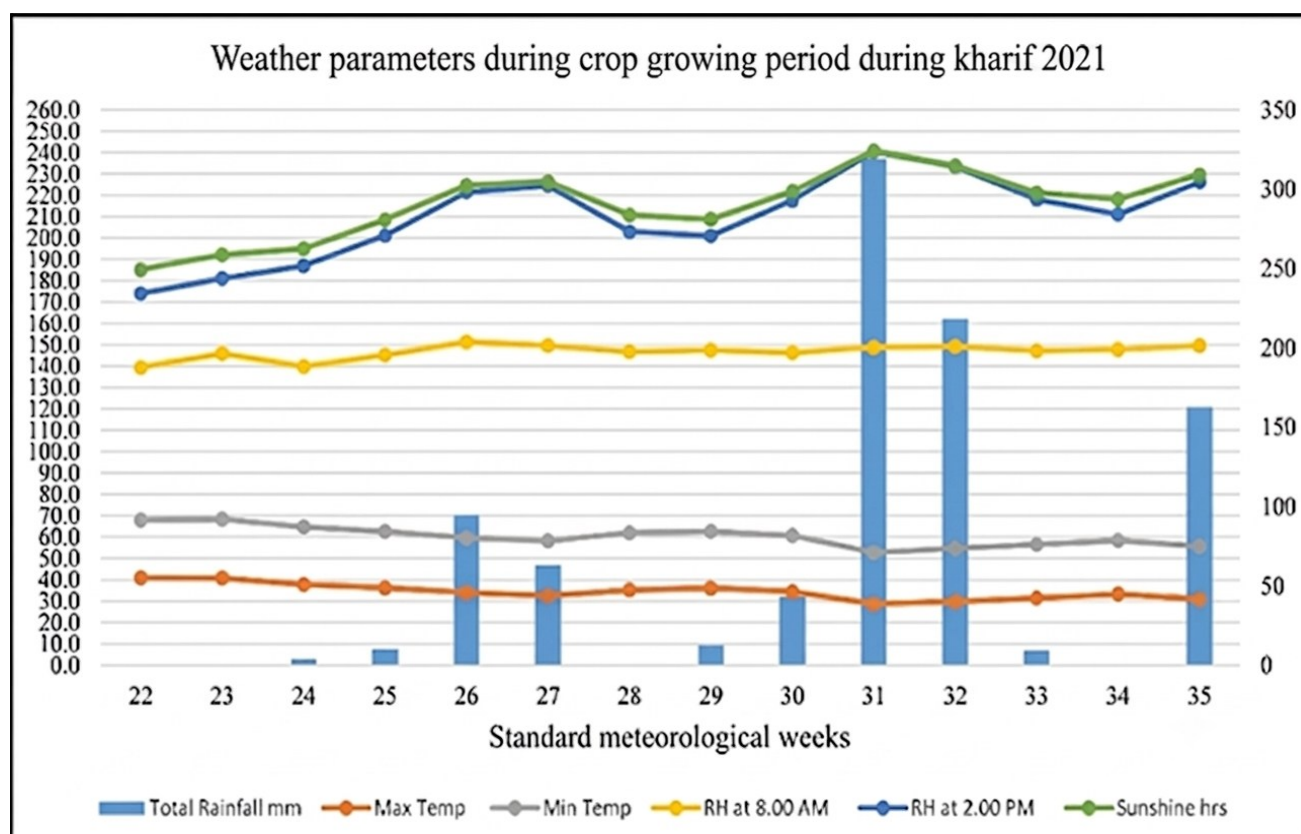
Particulars	Soil depth 0–15 cm	Method of analysis	References
1. Textural class		Loamy sand	
2. Chemical parameters			
I. Soil pH (1:2.5, Soil:Water)	7.46	Potentiometric method	(18)
II. EC (dS m ⁻¹) (1:2.5, Soil:Water)	0.21	Conductometric method	(18)
III. Organic carbon (%)	0.28	Rapid titration method	(19)
IV. Available N (kg/ha)	232.87	Alkaline potassium permanganate method	(22)
V. Available P ₂ O ₅ (kg/ha)	35.12	Olsen's method (spectrophotometric)	(21)
VI. Available K ₂ O (kg/ha)	280.20	Flame photometric method	(20)
Crude protein (%)		NIR feed and forage analyser (FOSS NIR system)	(20)
ADF and NDF		Forage fibre analysis	(23)
Zn content		Atomic absorption spectrophotometric method	(24)
Crude protein (%)		NIR feed and forage analyser (FOSS NIR system)	(20)

EC: electrical conductivity; ADF: acid detergent fibre; NDF: neutral detergent fibre; N: nitrogen; Zn: zinc.

Table 2. Treatment details of experiment

Treatment	Treatment's details
T ₁	0 kg ZnSO ₄ and FeSO ₄ /ha (control)
T ₂	10 kg ZnSO ₄ /ha followed by 0.5 % ZnSO ₄ foliar spray
T ₃	10 kg FeSO ₄ /ha followed by 0.5 % FeSO ₄ foliar spray
T ₄	10 kg ZnSO ₄ + 10 kg FeSO ₄ /ha followed by 0.5 % ZnSO ₄ + 0.5 % FeSO ₄ as foliar spray
T ₅	20 kg ZnSO ₄ /ha followed by 0.5 % ZnSO ₄ foliar spray
T ₆	20 kg FeSO ₄ /ha followed by 0.5 % FeSO ₄ foliar spray
T ₇	20 kg ZnSO ₄ + 20 kg FeSO ₄ /ha followed by 0.5 % ZnSO ₄ + 0.5 % FeSO ₄ as foliar spray

Foliar spray of zinc and iron done at 30 and 45 days after sowing.

**Fig. 1.** Weather parameters of Anand during crop growing period kharif 2020 season I.**Fig. 2.** Weather parameters of Anand during crop growing period kharif 2021 season II.

sowing seed treatment with a recommended insecticide/pesticide [Central Insecticides Board (CIB) approved] to control insects and pests during the crop-growing period. As a kharif crop, irrigation was not required; however, when long dry spells occurred, irrigation was applied at a depth of 5 cm per irrigation. During the crop growth period, the fodder sorghum crop was kept weed-free by one hand weeding and two interculturing operations to reduce crop-weed competition. A recommended weedicide was applied after sowing as a pre-emergence treatment throughout the experiment. Other recommended agronomical practices were adopted for fodder sorghum cultivation. The crop was harvested manually at the 50 % flowering stage for green fodder purposes. Foliar sprays of Zn and Fe were applied at 30 and 45 DAS. The Fe spraying solution was neutralised with lime water to reduce the scorching effect on the plant.

Growth attributes and green fodder yield

At different stages of crop growth, plant populations and growth parameters such as periodical plant height, number of tillers per meter row length, number of leaves per plant at harvest and green fodder yield were recorded. Growth parameters, including periodical plant height, number of tillers per meter row length, number of leaves per plant at harvest, were recorded from five randomly selected plants within the net plot area. Observation was recorded according to predetermined intervals i.e. plant height and number of leaves per plant at 20 DAS, 35 DAS and at harvest; plant population at 20 DAS; and number of tillers per meter row length at harvest. Fresh green fodder yield per plot was recorded from the net plot area (9.6 sq m²) and subsequently converted into quintals per hectare. To avoid the border effects, plants from the border rows were harvested first, after which the plants from the net plot area were harvested and the fresh green fodder yield was recorded.

Plant proximate (quality) analysis

Proximate (quality) analysis was performed on all collected samples using standard analytical methods. A 500 g of fresh sample was taken from each net plot area for proximate analysis, including crude protein, dry matter content, acid detergent fibre (ADF) and neutral detergent fibre (NDF). Each quality parameter was determined following its respective standard analytical procedure.

Dry matter content

A fresh sample of 500 g green forage was collected from each net plot, chopped into small pieces and air-dried for 3–4 days. The samples were then oven-dried at 60 °C until a constant weight was attained. The dry matter content (%) was calculated using the formula given below

$$\text{Dry matter content (\%)} = \frac{\text{Oven dried forage weight (g)}}{\text{Fresh forage weight (g)}} \times 100$$

Dry matter yield (q/ha)

The green forage yield (q/ha) obtained from the net plot area was multiplied by the respective dry matter percentage to calculate the dry matter yield (q/ha) for each treatment. The dry matter yield (q/ha) was calculated using the following formula:

$$\text{Dry matter yield (q/ha)} = \frac{\text{Green fodder yield (q/ha)} \times \text{Dry matter content (\%)}}{100}$$

Crude protein content (%)

Crude protein content was estimated from the powdered representative oven-dried samples using the NIR feed and forage analyser developed by the FOSS NIR system.

Crude protein yield (q/ha)

The crude protein yield was estimated by multiplying the crude protein content (%) by the dry matter yield using the formula given below and was expressed in q/ha.

$$\text{Crude protein yield (q/ha)} = \frac{\text{Dry matter yield (q/ha)} \times \text{Crude protein content (\%)}}{100}$$

Neutral detergent fibre content (%)

The thorough ground and mixed dry sample from each treatment were collected for the estimation of NDF content (25).

Acid detergent fibre content (%)

The thorough ground and mixed dry sample from each treatment was collected for the estimation of ADF content (25).

Determination of available zinc and iron in soil

The soil samples collected before sowing fodder sorghum were air-dried, properly crushed and passed through a 2 mm sieve. Diethylene triamine pentaacetic acid (DTPA)-extractable Zn and Fe were assessed by extracting a 10 g portion of the soil sample with 20 mL of DTPA extractant as described using wet digestion (20) (HNO₃:HClO₄ 4:1) followed by atomic absorption spectrophotometry.

Available Zn and Fe (mg/kg) in soil = Concentration of extractant on atomic absorption spectrophotometer (AAS) × dilution factor (2)

Determination of zinc and iron content in plant part (leaves and stalk)

For the analysis of Zn and Fe content in green fodder, including leaves and stalk (plant harvest at the 50 % flowering stage), a 0.5 g sample was digested using a diacid mixture (HNO₃:HClO₄ 4:1) as per the standard method as described using wet digestion (5) (HNO₃:HClO₄ 4:1) followed by atomic absorption spectrophotometry. After appropriate dilution, the concentrations of Zn and Fe in the digests were determined using an atomic absorption spectrophotometer.

Statistical analysis

Mean data on various parameters were collected from the individual net plot area and analysed using Fisher's analysis of variance (ANOVA) technique for a RCBD (26). The critical difference (CD) was used to compare treatment effects at $p < 0.05$.

Results and Discussion

Quality green fodder production is the primary source for dairy production because of its high palatability and digestibility. Among the different micronutrient treatments involving Zn and Fe through soil and foliar application on fodder sorghum, the response of different treatments on plant population was found to be non-significant (Table 3). This indicates that a uniform plant population was maintained in each plot during both seasons. Green fodder is an important economic component for dairy animals because of its high nutrient composition and palatability after 35 days. Periodic plant height at 20 and 35 days after sowing and at harvest was significantly affected by the application of Zn

Table 3. Effect of zinc and iron application on growth attributes of fodder sorghum

Treatment	Plant population		Plant height (cm)						Number of tiller per plant	
			At 20 DAS		At 35 DAS		At harvest			
	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II
T ₁	8.0 ^a	8.30 ^a	90.10 ^a	89.85 ^a	141.25 ^b	155.25 ^a	229.90 ^c	234.75 ^d	4.35 ^d	20.50 ^c
T ₂	7.8 ^a	7.75 ^a	96.80 ^a	96.75 ^a	158.50 ^a	152.10 ^a	222.00 ^c	248.80 ^{cd}	4.90 ^{cd}	22.15 ^{bc}
T ₃	7.8 ^a	8.00 ^a	90.50 ^a	90.50 ^a	162.75 ^a	155.55 ^a	230.00 ^c	253.80 ^c	5.68 ^{bc}	22.15 ^{bc}
T ₄	8.2 ^a	8.00 ^a	99.80 ^a	99.80 ^a	165.80 ^a	163.45 ^a	247.75 ^{ab}	273.35 ^b	6.30 ^{ab}	24.35 ^{ab}
T ₅	8.0 ^a	8.50 ^a	94.95 ^a	96.05 ^a	161.30 ^a	153.35 ^a	228.25 ^c	256.25 ^c	6.85 ^a	23.78 ^{bc}
T ₆	8.0 ^a	8.50 ^a	96.40 ^a	94.40 ^a	163.85 ^a	149.80 ^a	232.25 ^{bc}	253.00 ^c	6.85 ^a	22.58 ^{bc}
T ₇	8.4 ^a	8.60 ^a	93.30 ^a	93.30 ^a	161.95 ^a	146.05 ^a	252.00 ^a	294.75 ^a	7.15 ^a	27.85 ^a
LSD	NS	NS	NS	NS	13.68	NS	15.80	15.64	1.15	3.80

DAS: days after sowing; LSD: least significant difference; NS: non-significant.

and Fe treatments (Table 3). The effect of different treatments on plant height at 20 DAS was found to be non-significant during both seasons. At 35 DAS, the application of 10 kg ZnSO₄ + 10 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS (T₄) recorded significantly higher plant height (165.80 cm) than the rest of the treatments, except treatment T₁ (no application of fertiliser). However, the effect of treatments on plant height during the second season was found to be non-significant. At harvest, an application of 20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS (T₇) recorded the tallest plants (252.00 cm and 294.75 cm during the first and second seasons respectively). The control treatment (T₁) recorded the shortest plants (229.90 and 234.75 cm at harvest) among all treatments. Micronutrients are essential for plants, even though they are required in very small amounts. These nutrients play crucial roles in various physiological functions, often acting as cofactors in enzymatic reactions (27). The increase in plant height of fodder sorghum due to the application of Zn and Fe through soil and foliar application might be attributed to the role of Fe in essential metabolic processes, including respiration, photosynthesis, DNA synthesis and chlorophyll production. Increased Zn availability and absorption from the soil solution may have enhanced cytochrome synthesis, stabilised ribosomal fractions, accelerated cell division and promoted cell elongation.

The rising needs of cattle for feed cannot be met by proper fodder crop selection alone. Agronomic biofortification of Zn and Fe can enhance fodder crop growth and productivity. A significant response to treatment differences was observed with respect to the numbers of tillers per meter row length (Table 3). During both growing seasons, a significantly higher number of tillers (7.15 and 27.85) was reported in treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS). No application of Zn and Fe in fodder sorghum resulted in a lower number of tillers per meter row length (4.35 and 20.50 during first and second seasons respectively). The increase in the number of tillers per meter row length due to the application of Zn and Fe through soil and foliar application might be attributed to the fact

that Fe and Zn supplementation benefits sorghum, as these minerals act as cofactors for many enzymes involved in various metabolic processes, including protein and carbohydrate metabolism. The Zn and Fe help sorghum crops grow and develop vigorously by activating these enzymes, which makes nutrients easier to assimilate, produce energy and improve overall metabolic efficiency. Another possible reason is that adequate levels of micronutrients ensure efficient photosynthesis activity, leading to enhanced energy production and biomass accumulation (27). A higher concentration of Zn in the soil rhizosphere and its better utilisation through foliar feeding may also have contributed to increased plant height and leaf area index, which helped enhance the photosynthetic rate of the plant, ultimately resulting in greater tiller formation (27–32).

Significantly taller plants with a higher number of leaves per plant were significantly affected by the combined application of Zn and Fe through soil and foliar applications (Table 4). The number of leaves per plant increased with increasing levels of Zn and Fe applied through soil and foliar application in forage sorghum. Data presented in Table 4 indicated that the effect of different Zn and Fe treatments was non-significant at 20 DAS during both growing seasons. Significantly, the highest number of leaves per plant (35.50 and 22.75 at harvest during season I and II respectively) was observed in treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS). The higher number of leaves per plant might be because Zn and Fe are necessary components involved in the synthesis of chlorophyll, which is essential for photosynthesis (28).

The experiment results revealed that fresh green fodder yield of sorghum was significantly improved by the combined application of Zn and Fe micronutrients by soil and foliar application (Table 4). The data presented in Table 4 indicated that, among the various Zn and Fe treatments, a significantly higher green fodder yield of 826.39 q/ha was recorded during season I, while the highest green fodder yield of 575.00 q/ha was recorded during season II in treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha

Table 4. Effect of zinc and iron application on yield attributable, green fodder, dry fodder and crude protein yield of fodder sorghum (two seasons)

Treatment	No. of leaves per plant				Green fodder yield (q/ha)		DMY (q/ha)		CPY (q/ha)	
	At 20 DAS	At harvest	At 20 DAS	At harvest						
	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II		
T ₁	5.75 ^a	25.35 ^c	5.95 ^a	18.70 ^c	517.36 ^c	295.75 ^d	142.4 ^d	72.64 ^d	8.38 ^c	4.37 ^d
T ₂	5.95 ^a	24.00 ^c	5.75 ^a	20.85 ^b	593.75 ^c	366.75 ^c	196.6 ^c	104.84 ^c	11.11 ^{bc}	6.33 ^{cd}
T ₃	5.75 ^a	30.45 ^b	6.15 ^a	20.30 ^{bc}	631.94 ^{bc}	387.50 ^{bc}	207.6 ^c	128.29 ^{bc}	11.80 ^b	8.98 ^b
T ₄	6.70 ^a	28.85 ^{bc}	7.05 ^a	21.20 ^{ab}	788.19 ^a	546.00 ^a	266.6 ^{ab}	185.89 ^a	15.36 ^a	11.67 ^a
T ₅	5.55 ^a	30.30 ^b	5.55 ^a	20.95 ^b	736.11 ^{ab}	422.75 ^b	219.3 ^{bc}	133.18 ^b	11.09 ^{bc}	8.07 ^{bc}
T ₆	5.60 ^a	31.80 ^{ab}	6.25 ^a	20.20 ^{bc}	725.69 ^{ab}	404.00 ^{bc}	225.1 ^{abc}	134.09 ^b	11.18 ^{bc}	8.10 ^{bc}
T ₇	5.75 ^a	35.50 ^a	6.40 ^a	22.75 ^a	826.39 ^a	575.00 ^a	273.8 ^a	196.08 ^a	12.83 ^{ab}	12.21 ^a
LSD	NS	4.90	NS	1.67	115.42	45.91	48.87	27.60	3.04	2.38

DMY: dry matter yield; CPY: crude protein yield; DAS: days after sowing; LSD: least significant difference; NS: non-significant.

followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS) compared to the other treatments. During both seasons, treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray) recorded 59.73 % and 94.42 % higher green fodder yield than the control treatment (T₁). The minimum green fodder yield (517.36 and 295.75 q/ha) was recorded in treatment T₁ (0 kg ZnSO₄ and FeSO₄ q/ha). Application of Zn and Fe through soil as well as foliar feeding reported higher green fodder yield of sorghum, which might be because both Zn and Fe help plants absorb and translocate other vital nutrients. It is possible that the foliar spray application of Zn fertiliser contributed to this notable increase in fodder sorghum yield. Proteins and amino acids are synthesised using Zn, while Fe is required for the formation of chloroplasts and mitochondrial proteins. In general, Fe and Zn increase sorghum crop growth by promoting stress tolerance, root development, photosynthesis, enzyme activation and nutrient absorption. The optimisation of crop production and yield necessitates the maintenance of sufficient concentrations of these micronutrients in the soil and their optimal accessibility to sorghum plants (28, 33). Another reason might be that Zn and Fe have critical roles in enhancing nutrient absorption and utilisation efficiency, which further leads to higher plant growth and productivity, thereby accounting for most of the increased fodder sorghum production. Increased application of Zn and Fe ensured that these nutrients remained available to crop plants throughout the crop growth period (33, 34). According to the previous findings, Zn boosts photosynthetic efficiency, which in turn produces more dry matter (16, 35, 36). Zinc application-induced increases in plant height, leaf area index and the cumulative impact of a notable rise in the yield of dry fodder and green fodder can also be linked to greater dry matter production.

The results indicating the effects of Zn and Fe on dry matter content, crude protein content, dry matter yield and crude protein yield of fodder sorghum are presented in Tables 4 and 5. Significantly higher dry matter yield (273.80 and 196.08 q/ha) was recorded in treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS) during both seasons. Similarly, the highest crude protein yield (15.36 and 12.21 q/ha) was recorded in treatment T₄ (10 kg ZnSO₄ + 10 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray at 30 and 45 DAS) during season I and in treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray at 30 and 45 DAS), during season II.

The significant differences observed with respect to dry matter content and crude protein content of fodder sorghum are presented in Table 5. The data indicated that the effect of different Zn and Fe treatments on dry matter content was significant during seasons I and II, whereas the response of different treatments on crude protein content was found to be non-significant during both

seasons (Table 5). In season I, the application of 10 kg ZnSO₄ + 10 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS (T₄) recorded the highest dry matter content (33.68 %). In season II, treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS) recorded significantly higher dry matter content (34.03 %) over the rest of the treatments, except T₃, T₄, T₅ and T₆. This might be due to the catalytic actions of Fe and Zn, which accelerate hormone production through the activation of tryptophan, a precursor of indole-3-acetic acid (auxin), protein synthesis and other growth processes, thereby leading to increased accumulation of dry matter (37, 38).

Because it has a high lignin content, ADF is a rough indicator of forage digestibility. A higher ADF content lowers feed dry matter digestibility. The proportion of NDF in feed indicates the quantity of cell wall constituents and the cell wall percentage can be used to assess forage digestibility. The NDF includes structural cell wall components such as cellulose, hemicellulose, lignin and cutin, which are slowly digestible fractions. Therefore, a higher NDF content is generally associated with reduced dry matter intake in ruminants. The ADF and NDF contents of fodder sorghum were significantly affected by the application of Zn and Fe, as presented in Table 5. Significantly lower ADF content (34.75 % and 51.00 %) was recorded in treatment T₄ (10 kg ZnSO₄ + 10 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray) during both seasons, while, treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray at 45 DAS) reported lower NDF (68.20 % and 60.30 %) during both seasons respectively. Perusal data reported that ADF content was 17.12 % and 13.23 % lower (T₄: 10 kg ZnSO₄ + 10 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray) compared to its higher value treatment (T₃: 10 kg FeSO₄/ha followed by 0.5 % FeSO₄ foliar spray), whereas NDF content 7.95 % and 15.80 % lower than other treatments. This might be due to application of RDF and Zn spray at vegetative and reproductive stage which reduces the soluble carbohydrate content in plant tissue and promotes protein synthesis (38–40).

Data reported in Table 6 indicated that the application of Zn and Fe influenced the available Zn and Fe status after harvest, as well as their content and uptake by the plant. Perusal of the data reported in Table 6 indicated that the application of 10 kg ZnSO₄ + 10 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray at 30 and 45 DAS (T₄) reported higher available Zn content (3.84 ppm) during first season, while in the second season, treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray at 30 and 45 DAS) reported higher available Zn content (4.90 ppm). The available Fe status after harvest of the crop, as reported in Table 6, revealed that the application of 20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 %

Table 5. Effect zinc and iron application on proximate parameters of fodder sorghum (two seasons)

Treatment	DM (%)		CP (%)		ADF (%)		NDF (%)	
	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II
T ₁	27.55 ^c	24.53 ^c	5.89 ^a	6.03 ^a	39.75 ^a	54.75 ^{ab}	73.15 ^b	69.24 ^a
T ₂	33.13 ^{ab}	28.50 ^{bc}	5.77 ^a	6.04 ^a	38.75 ^a	57.75 ^a	72.04 ^b	69.21 ^a
T ₃	32.83 ^{ab}	33.08 ^a	5.67 ^a	6.94 ^a	40.75 ^a	55.50 ^{ab}	71.94 ^b	69.20 ^a
T ₄	33.68 ^a	33.95 ^a	5.86 ^a	6.27 ^a	34.75 ^c	51.00 ^{cd}	68.20 ^a	60.30 ^a
T ₅	29.90 ^{bc}	31.45 ^{ab}	4.98 ^a	6.06 ^a	38.25 ^{abc}	52.50 ^{bc}	72.50 ^b	69.42 ^a
T ₆	30.90 ^{ab}	33.30 ^a	4.96 ^a	6.02 ^a	38.50 ^{ab}	54.50 ^b	71.32 ^b	69.51 ^a
T ₇	33.05 ^{ab}	34.03 ^a	4.72 ^a	6.25 ^a	35.00 ^{bc}	49.00 ^d	67.76 ^a	59.79 ^a
LSD	3.28	4.10	NS	NS	3.57	3.03	2.70	1.48

DM: dry matter; CP: crude protein; ADF: acid detergent fibre; NDF: neutral detergent fibre; LSD: least significant difference; NS: non-significant.

Table 6. Effect of zinc and iron application on zinc and iron content and soil micronutrient status (two seasons)

Treatment	Available Zn in soil (ppm)		Zn content in plant (ppm)		Available Fe in soil (ppm)		Fe content in plant (ppm)		Zn uptake (g/ha)		Fe uptake (g/ha)	
	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II
T ₁	1.58 ^b	1.68 ^e	33.85 ^c	34.86 ^d	1.44 ^e	1.91 ^e	101.13 ^f	105.31 ^e	32.78	56.96	107.09	171.95
T ₂	4.26 ^a	4.07 ^c	90.95 ^b	91.20 ^c	2.57 ^d	2.85 ^d	131.08 ^e	133.92 ^d	105.13	179.04	175.44	258.12
T ₃	1.67 ^b	1.96 ^d	38.52 ^c	38.77 ^d	3.15 ^{bc}	3.14 ^c	144.20 ^d	149.44 ^{bc}	49.70	80.04	214.96	300.35
T ₄	3.84 ^a	4.46 ^b	95.24 ^b	97.49 ^c	3.29 ^b	3.34 ^b	157.01 ^c	159.71 ^b	171.36	244.89	265.56	403.10
T ₅	3.71 ^a	4.39 ^b	120.91 ^a	131.16 ^a	2.90 ^c	2.94 ^d	146.08 ^{cd}	148.01 ^c	174.52	265.53	216.71	320.44
T ₆	1.74 ^b	1.92 ^d	40.16 ^c	41.19 ^d	3.39 ^{ab}	3.46 ^b	185.21 ^b	189.54 ^a	51.06	89.50	340.22	407.91
T ₇	3.73 ^a	4.90 ^a	115.42 ^a	118.16 ^b	3.63 ^a	3.74 ^a	201.84 ^a	199.70 ^a	215.84	290.27	401.88	509.45
LSD	0.65	0.14	10.90	7.31	0.28	0.12	11.66	10.83	–	–	–	–

LSD: least significant difference; Zn: zinc; Fe: iron.

ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS (T₇) noted significantly higher available Fe content (3.63 and 3.74 ppm, in the first and second seasons respectively). Minimum available Zn and Fe after harvest was reported in Table 6. Mean data indicated that no application of Zn and Fe (0 kg ZnSO₄ and FeSO₄/ha) noted significantly minimum available Zn (1.58 and 1.68 ppm) and Fe (1.44 and 1.91 ppm).

The Zn and Fe contents of fodder sorghum were influenced by various Zn and Fe treatments (Table 6). Analysis of the mean data presented in Table 6 indicated that the application of 20 kg ZnSO₄/ha followed by 0.5 % ZnSO₄ foliar spray at 30 and 45 DAS (T₅) reported significantly higher Zn content (120.91 and 131.16 ppm). Iron content of fodder sorghum (201.84 and 199.70 ppm) was significantly higher in treatment T₇ (20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS). Lower Zn (33.85 and 34.86 ppm) and Fe (101.13 and 105.31 ppm) contents in fodder sorghum were observed in treatment T₁ (0 kg ZnSO₄ and FeSO₄/ha).

Data reported in Table 6 indicated that the application of 20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as a foliar spray at 30 and 45 DAS (T₇) recorded significantly higher Zn uptake (215.84 and 290.27 g/ha during season I and II respectively) by fodder sorghum. Significantly higher Fe uptake (401.88 and 509.45 g/ha during season I and II respectively). Control treatment T₁ (0 kg ZnSO₄ and FeSO₄ q/ha) noted significantly minimum Zn (32.78 and 56.96 g/ha) and Fe (107.09 and 171.95 g/ha) during season I and II. The higher nutrient uptake in grain was mainly attributed to higher dry matter production, grain and fodder yield, which can be related to better and continuous availability of nutrients in root zone for longer period of crop growth (41).

Conclusion

Soil and foliar application of micronutrients are key agronomic practices for enhancing the nutrient content of plants that can be achieved through “biofortification”. These methods help increase the availability and uptake of essential micronutrients, which are vital for optimal plant growth and development. When micronutrients are effectively supplied through soil and foliar sprays, their concentration in edible plant parts, such as fodder and food crops, increases significantly. This enhancement of nutrient levels in crops is a fundamental component of biofortification, a strategy aimed at improving the nutritional quality of agricultural produce.

The significance of this study lies in its potential to address widespread micronutrient deficiencies in both human and livestock populations. By improving the micronutrient content of fodder, feed quality for dairy animals can be enhanced, leading to better animal health, improved milk production and overall dairy productivity. Additionally, biofortified crops contribute to food and feed security by providing nutrient-dense produce without requiring changes in dietary habits or costly supplementation programs. Therefore, this research supports sustainable agricultural practices that benefit crop performance, livestock productivity and nutritional outcomes for consumers. From the results of three years studies, it can be concluded that application of 20 kg ZnSO₄ + 20 kg FeSO₄/ha followed by 0.5 % ZnSO₄ + 0.5 % FeSO₄ as foliar spray at 45 days after sowing (DAS) reported significantly higher growth, yield attributes and green fodder yield of fodder sorghum. Quality parameters of fodder sorghum are also positively affected by the soil application of ZnSO₄ and FeSO₄ each 20 kg/ha along with 0.5 % ZnSO₄ and FeSO₄ at 45 DAS. Balance utilisation of all macro and micronutrients in appropriate quantity helps to improve green fodder yield and quality and nutrient status in soil and plant.

Future research

As per present study and quality requirements, future research on fodder crop biofortification should focus on developing sustainable and efficient strategies to enhance the micronutrient content of fodder crops without compromising yield and quality. Greater emphasis should be placed on identifying fodder crop varieties with higher nutrient-use efficiency and better responsiveness to micronutrient application through soil and foliar methods. Breeding programs and molecular approaches can be explored to develop biofortified fodder varieties enriched with essential micronutrients such as zinc, iron, copper and selenium.

Further studies are needed to optimise the dosage, timing and method of micronutrient application to maximise nutrient uptake and translocation in fodder crops. Integrated nutrient management approaches combining chemical fertilisers, organic manures and microbial inoculants should be evaluated for their role in improving biofortification efficiency. Research should also investigate the interaction between micronutrients and soil properties, climate and crop management practices.

In addition, future studies should assess the impact of biofortified fodder on animal health, feed efficiency, milk yield and milk quality under field conditions. Long-term studies are required to

evaluate the economic feasibility and environmental sustainability of fodder crop biofortification. Strengthening farmer awareness and technology transfer will also be crucial for the large-scale adoption of biofortified fodder crops, ultimately contributing to improved livestock productivity and nutritional security.

Acknowledgements

The authors are grateful to the Director of Research, Anand Agricultural University, for the technical and financial support provided during the course of the experiment. The authors also sincerely thank the Research Scientist and Head, Main Forage Research Station, Anand Agricultural University, Anand, for valuable technical guidance. They further express their gratitude to the Associate Research Scientist and Head, Micronutrient Research Project, ICAR Unit-9, for conducting the plant chemical analyses and providing facilities for micronutrient analysis. The authors are also thankful to the Associate Research Scientist and Head, Micronutrient Project, Anand Agricultural University, Anand, for their support and assistance throughout the study.

Authors' contributions

PHK conducted the experiment and collecting all primary data. PHK also carried out the analysis and interpretation of the data and contributed to the writing and finalisation of the manuscript. RPH participated in the biochemical analysis of all quality parameters and contributed to the writing and finalisation of the manuscript. Both authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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