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Effects of farmyard manure and zinc application on yield and quality of kharif fodder sorghum

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Abstract

A field study was conducted during the kharif season of 2024 at the Main Forage Research Station, Anand Agricultural University, Anand, Gujarat, to assess the effects of farmyard manure (FYM) and zinc application on the yield and quality of kharif fodder sorghum. The experiment comprised twelve treatment combinations involving two FYM levels (0 and 10 t/ha) and six zinc treatments: Z_1 (0 kg Zn/ha), Z_2 (12.5 kg Zn/ha), Z_3 (25 kg Zn/ha), Z_4 (12.5 kg Zn/ha followed by zinc-solubilising bacteria (ZnSB) soil application), Z_5 (12.5 kg Zn/ha followed by 0.05 % Zn foliar application) and Z_6 (12.5 kg Zn/ha followed by ZnSB soil application and 0.05 % Zn foliar application). The experiment was conducted in a factorial randomised block design (FRBD) with three replications. Application of 10 t FYM/ha significantly increased green fodder yield (421.50 q/ha), dry matter yield (128.93 q/ha), crude protein yield (11.94 q/ha), plant zinc content (29.91 mg/kg) and zinc uptake (41.07 g/ha), along with post-harvest available soil zinc (2.96 mg/kg) and ZnSB count, compared with the control. Among zinc treatments, Z_6 produced higher green fodder yield (376.33 q/ha), dry matter yield (123.36 q/ha), crude protein yield (11.59 q/ha) and zinc content (29.64 mg/kg), while Z_5 and Z_6 recorded higher post-harvest available zinc (2.75 and 2.84 mg/kg respectively) and zinc uptake (41.99 g/ha) respectively. The FYM × zinc interaction was significant. F_2Z_5 produced higher dry matter (180.73 q/ha) and crude protein yield (18.61 q/ha), whereas F_2Z_6 recorded higher zinc uptake (64.03 g/ha) and post-harvest available zinc (3.40 mg/kg).

Keywords: crude protein content; crude protein yield; dry matter content; dry matter yield; FYM; green fodder yield; zinc

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1. Introduction

India remains predominantly agrarian, with nearly 70 % of its population residing in rural areas and depending largely on agriculture and allied activities for sustenance. Livestock, as an integral component of this system, plays a crucial role in rural livelihoods and India ranks first globally in terms of total livestock population (1).

Agriculture and animal husbandry are culturally, religiously and economically intertwined with the intricate fabric of human society, as mixed farming and livestock rearing are vital elements of rural life (2, 3). With the growing demand for animal products, the importance of supplying livestock with nutritious, organic fodder is increasingly recognised not only for enhancing animal health and productivity but also for promoting sustainable agricultural practices through organic waste recycling. The livestock industry cannot be sustained in the long term without an adequate supply of high-quality feed and fodder. To ensure an abundant supply of nutritious fodder, appropriate nutrient management practices must be implemented (1).

However, the sector faces a persistent challenge in the form of inadequate quality feed, particularly during lean periods. This shortage hampers livestock productivity and increases the cost of milk and meat production. Current estimates indicate a national annual forage requirement of 1325.7 mt, including 816.8 mt of green fodder and 508.9 mt of dry fodder. However, only 978.7 mt are produced (525.5 mt green fodder and 453.2 mt dry fodder), resulting in significant deficits of 35.6 % in green fodder, 10.95 % in dry residues and 44 % in concentrate feed ingredients (4). Addressing this gap is imperative for improving livestock efficiency and ensuring the long-term viability of the agricultural sector.

Sorghum (*Sorghum bicolor* L. Moench), commonly referred to as the “King of Millets,” is an important cereal crop cultivated for both food and fodder. It is a versatile crop that is widely grown because of its adaptability to diverse agro-climatic conditions and its significant role in feed, fodder and biofuel production (5). In 2023–24, globally, sorghum

was the fifth most important cereal crop after rice, wheat, maize and barley, whereas in India it ranked fourth (6). In India, sorghum was cultivated over 3.97 million hectares, producing 4.4 mt. Known for its high biomass production and nutrient demand, sorghum requires adequate nitrogen for optimal growth, as nitrogen plays a central role in protein synthesis and biomass accumulation (7). Sorghum serves as a primary food source for 19.5 % of the global population and 27 % of the Indian population (6).

Organic inputs such as farmyard manure (FYM) are vital for sustainable agriculture. Farmyard manure not only supplies essential nutrients, including macro and micronutrients, but also improves soil structure, microbial activity and long-term fertility. Although its nutrients are slow-releasing, they support sustained plant growth and help maintain soil health (8, 9).

Another critical issue is the widespread zinc (Zn) deficiency in Indian soils, largely due to intensive farming and the exclusive reliance on chemical fertilisers. Nearly half of global cereal-growing soils lack plant-available Zn (10), which adversely affects crop yields and contributes to Zn deficiency in human diets, affecting nearly 30 % of the global population (11, 12). Zinc is essential for enzyme activity, reproductive development and immune response in both plants and humans.

Hidden hunger, or micronutrient deficiency, retards the growth and development of both crops and humans. Micronutrients follow a pathway from soil through crops and food to the human body (13). Agronomic biofortification, particularly through Zn fertilisation, is a promising approach to enhance the Zn content of fodder and food crops through fertiliser application (i.e. ferti-fortification) (14), as Indian soils are deficient in micronutrients and their deficiency can be corrected in plants as well as in animals through the food chain. This method offers a practical solution for improving fodder quality and addressing micronutrient malnutrition; research has confirmed a strong correlation between soil micronutrient availability and their accumulation in fodder crops, particularly for Zn (15, 16).

2. Materials and Methods

Location and weather description

The experiment was conducted at Plot J-7 of the Main Forage Research Station Farm, Anand Agricultural University, Anand, Gujarat, during the kharif season of 2024. Anand is located at an altitude of 45.1 m above mean sea level, at 22°35′ N and 72°56′ E. It is situated approximately 70 km inland from the Arabian Sea, which contributes to its semi-arid subtropical climate characterised by hot and relatively dry summers.

During the crop season, the maximum temperature ranged from 30.76 °C to 36.04 °C, while the minimum temperature varied between 17.20 °C and 26.17 °C. The mean temperature ranged from 24.84 °C to 30.21 °C. Average relative humidity fluctuated between 53.77 % and 84.71 %, daily sunshine duration ranged from 2.19 to 9.94 hr, daily rainfall varied from 0 to 127.20 mm and the average wind speed ranged from 1.55 to 6.27 km/hr (Fig. 1).

Soil fertility status

Soil samples were collected from five to six randomly selected locations in the experimental field before sowing and combined to form a composite sample for determining initial physico-chemical properties of the soil (Table 1). The soil, classified as loamy sand, is locally referred to as "Goradu" soil. Before experiment sowing composite soil sample was taken from experiment area to know soil nutrient status and its result indicated that the experimental soil is low in organic carbon (C) (0.42 %), available nitrogen (N) (241.12 kg/ha) and available phosphorus (P) (21.54 kg/ha), but a medium status of available potassium (K) (245.25 kg/ha). The initial soil pH, electrical conductivity (EC) and available Zn were 8.31, 0.18 dS/m and 1.02 mg/kg respectively. The initial soil microbial count was 5.7×10^4 (4.75) cfu/g soil and the initial Zn solubilising bacteria (ZnSB) count was 3.1×10^3 (3.49) cfu/g soil.

Treatment details

Crop husbandry and fertiliser schedule

The experiment was conducted using a factorial randomised block design (FRBD) with three replications. Twelve treatment combinations were evaluated, comprising two FYM levels, F_1 (0 t FYM/ha) and F_2 (10 t FYM/ha) and six Zn treatments: Z_1 (0 kg Zn/ha), Z_2 (12.5 kg Zn/ha), Z_3 (25 kg Zn/ha), Z_4 (12.5 kgZn/ha followed by ZnSB soil application), Z_5 (12.5 kg Zn/ha followed by 0.05 % Zn foliar application) and Z_6 (12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application), Foliar application of 0.05 % zinc sulphate ($ZnSO_4$) was done at 30 and 45 days after sowing (DAS) and ZnSB soil application was done after first irrigation.

The fodder sorghum variety, GAFS 12 (Gujarat Anand Fodder Sorghum 12), was used in the experiment. Sowing was carried out at a line spacing of 30 cm using a seed rate of 80 kg/ha. Standard recommended agronomic practices were followed during the crop growth period, including one interculture and two hand weeding during the initial growth stage.

The recommended dose of fertiliser (RDF) of fodder sorghum was 80:40:00 kg/ha. Farmyard manure was incorporated at 15 DAS in the respective treatments. The RDF, i.e. N and P, was applied through soil application, while Zn was applied through soil and foliar application according to the schedule of spraying. Fifty per cent of the N (40 kg N/ha) and the entire P dose (40 kg P_2O_5/ha) were applied as a basal dose through urea and single superphosphate respectively. The remaining 25 % of the N (20 kg N /ha) was applied at 30 DAS and the remaining 25 % (20 kg N /ha) was applied at 45 DAS. According to the Zn treatments, zinc sulphate heptahydrate was applied as a basal soil application and foliar Zn was applied at 0.05 % at 30 and 45 DAS. Zinc-solubilising bacteria were applied to the soil after the first irrigation.

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Table 1. Methods used for soil and plant analysis

Sl. No.	Parameters	Method	References
A	Soil analysis		
1	pH (1:2.5 soil:water)	Potentiometric method	(18)
2	Electrical conductivity (1:2.5 soil:water)	Conductometric method	(18)
3	Organic carbon (OC)	Wet oxidation method	(19)
4	Available N (kg/ha)	Alkaline $KMnO_4$ method	(20)
5	Available P_2O_5 (kg/ha)	Olsen's method (0.5 M $NaHCO_3$ extractable, pH 8.5)	(21)
6	Available K_2O (kg/ha)	Neutral normal NH_4OAc extractable method	(18)
7	Available Zn	Atomic absorption spectrophotometric method	(22)

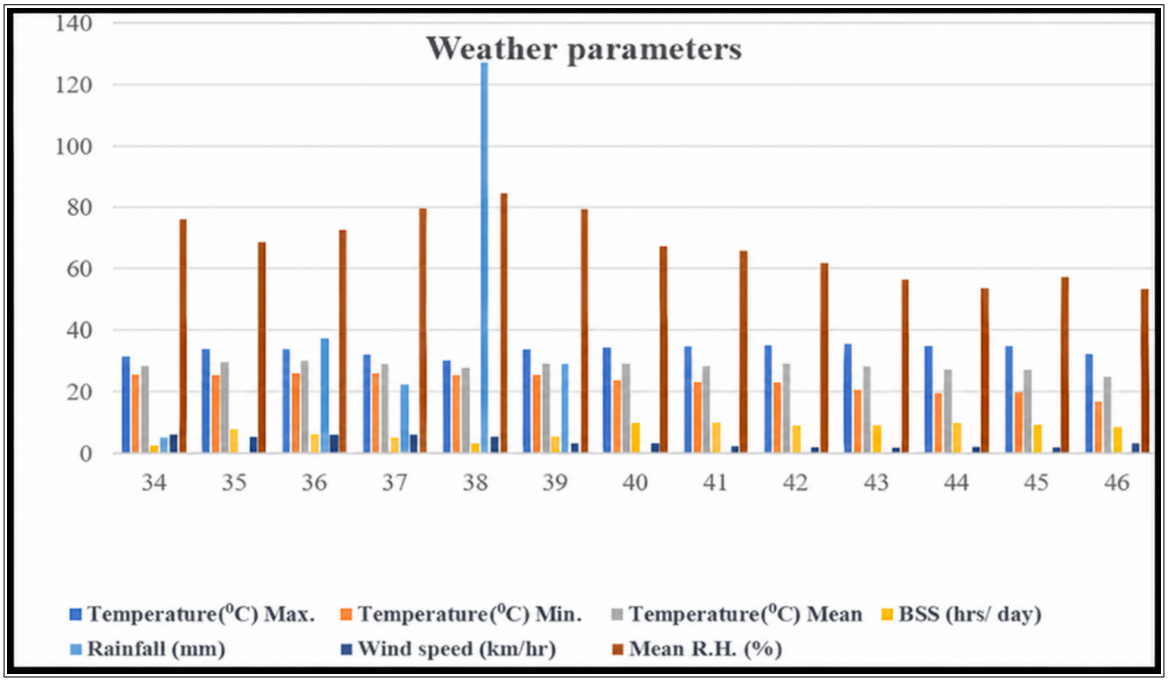


Fig. 1. Mean weekly weather parameters recorded during the experimental period.

Experimental observations and statistical analysis

All recorded parameters were subjected to statistical analysis following the standard methodology (17). The experimental data were analysed using analysis of variance (ANOVA) under FRBD. This statistical approach enabled effective comparison of treatment means and provided a sound basis for determining the significance of differences among treatments. Methods used for soil analysis, plant proximate analysis and soil microbial status are given in Tables 1 and 2.

Table 2. Proximate analysis, zinc content and soil microbial population

A	Plant analysis		
1	Crude protein (%)	NIR feed and forage analyser (FOSS NIR system)	(18)
2	Acid detergent fibre and neutral detergent fibre		(23)
3	Zn content	Atomic absorption spectrophotometric method	(22)
4	Hydrocyanic acid (ppm)	Picric acid method	(24)
B	**Microbial analysis**		
1	Total initial) count (cfu/g soil)	Serial dilution method	(25)
2	ZnSB count (cfu/g soil)	Serial dilution method	(25)

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3. Results and Discussion

Effect of FYM

Plant height and number of leaves per plant of fodder sorghum were influenced by FYM application. Data reported in Table 3 indicated that application of 10 t FYM/ha (F_2) resulted in significantly higher plant height at 25 DAS, 50 DAS and harvest (63.78, 141.36 and 237.67 cm respectively). Similarly, the number of leaves per plant at 50 DAS and harvest (7.29 and 12.27 respectively) was significantly higher under F_2, whereas the effect of FYM on the number of leaves per plant at 25 DAS was found non-significant. The increase in plant height and number of leaves per plant with FYM application may be attributed to its gradual release of essential nutrients, which supports sustained vegetative growth, cell division and elongation, resulting in taller plants (26, 27). Farmyard manure also supplies a wide range of macro- and micronutrients, particularly N and P, through gradual mineralisation, thereby promoting leaf initiation and expansion during the later stages of crop growth (28).

Data presented in Table 3 showed that application of 10 t FYM/ha resulted in a significantly higher leaf-stem ratio of fodder sorghum at harvest (0.56) than the F_1 (no manure) treatment. Farmyard manure gradually releases essential nutrients such as N and P, which promote leaf initiation and expansion, leading to a higher proportion of leaves relative to stems (29).

Perusal of the data presented in Table 3 revealed that application of 10 t FYM/ha recorded a significantly higher green fodder yield (421.50 q/ha) than the control treatment. The increase in green fodder yield may be attributed to the continuous availability of macro- and micronutrients throughout the crop growth period. Improved plant height, number of leaves per plant and leaf: stem ratio also contributed to greater biomass accumulation, ultimately increasing green fodder yield (30, 31). Application of FYM might improve overall growth and yield-attributing characters. Furthermore, incorporation of FYM into the soil provides a continuous supply of plant nutrients, particularly macro- and micronutrients, while improving the physicochemical and biological properties of the soil. These improvements enhance nutrient uptake and photosynthetic activity, leading to greater accumulation of photosynthates and their translocation to the sink through an improved source–sink relationship (32).

Mean data noted in Table 3 indicated that dry matter content, dry matter yield, crude protein content and crude protein yield of fodder sorghum were influenced by FYM application. Application of 10 t FYM/ha resulted in significantly higher dry matter content (29.91 %), dry matter yield (128.93 q/ha), crude protein content (8.76 %) and crude protein yield (11.94 q/ha) than the control treatment (F_1: 0t FYM/ha). Farmyard manure serves as a source of primary, secondary and micronutrients required for plant growth. It also provides a continuous source of energy for heterotrophic microorganisms, thereby increasing nutrient availability and improving crop quality (32–36). The increase in dry matter yield with FYM application may be attributed to the gradual release of a broad spectrum of essential nutrients, ensuring sustained nutrient uptake during the critical growth stages of the crop and promoting greater dry matter accumulation (32).

The effect of FYM application on ADF (acid detergent fibre) and NDF (neutral detergent fibre) was found to be significant. Data reported in Table 4 revealed that an application of 10 t FYM/ha recorded higher ADF (35.04 %) and NDF (65.25 %) contents than the control treatment F_1 (0 t FYM/ha). Farmyard manure boosts soil microbial activity, which accelerates the breakdown of lignin and cellulose, primary contributors to ADF. This microbial decomposition leads to lower ADF content in plant tissues, improving fodder digestibility (37, 38).

Table 3. Effect of FYM and zinc on growth attributes, yield and quality of fodder sorghum

Treatments	Plant height (cm)			Number of leaves per plant			leaf-stem ratio	Green fodder yield (q/ha)	Dry matter content (%)	Dry matter yield (q/ha)	Crude protein content (%)	Crude protein yield (q/ha)
	25 DAS	50 DAS	At harvest	25 DAS	50 DAS	At harvest						
FYM (t/ha)												
F_1	59.60	132.91	221.39	3.57	6.57	11.40	0.45	261.56	22.62	60.74	6.52	4.06
F_2	63.78	141.36	237.67	3.74	7.29	12.27	0.56	421.50	29.91	128.93	8.76	11.94
S.Em. ±	1.32	1.97	4.64	0.11	0.11	0.16	0.015	13.39	0.46	3.63	0.16	0.37
C.D. (p=0.05)	3.89	5.78	13.62	NS	0.33	0.47	0.044	39.28	1.36	10.65	0.46	1.10
Zinc application												
Z_1	60.27	130.77	208.67	3.60	6.33	10.97	0.35	287.17	15.70	46.75	5.87	2.74
Z_2	59.17	139.63	220.67	3.80	6.67	11.93	0.43	299.17	18.42	56.24	6.78	3.99
Z_3	63.27	134.10	236.67	3.53	7.30	12.07	0.55	367.00	30.67	114.51	8.15	9.83
Z_4	62.47	132.27	227.83	3.60	6.90	11.80	0.51	350.00	29.95	105.48	7.80	8.38
Z_5	61.97	140.33	238.33	3.66	6.97	11.83	0.59	369.50	31.37	122.67	8.49	11.48
Z_6	63.00	145.70	245.00	3.72	7.40	12.40	0.58	376.33	31.47	123.36	8.76	11.59
S.Em. ±	2.29	3.41	8.04	0.19	0.19	0.28	0.026	23.19	0.80	6.29	0.27	0.65

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C.D. (*p*=0.05)	NS	10.01	23.60	NS	0.58	0.82	0.076	68.04	2.35	18.45	0.81	1.92
Z × F	NS	NS	NS	NS	NS	NS	Sig.	NS	Sig.	Sig.	Sig.	Sig.
C.V. (%)	9.13	6.10	8.59	13.03	7.05	5.82	12.64	16.64	7.50	16.25	8.89	20.04

DAS: Days after sowing; CD: Critical difference; FYM: Farmyard manure.

Table 4. Effect of farmyard manure and zinc on quality and after-harvest soil nutrient status of fodder sorghum

Treatments	ADF (%)	NDF (%)	HCN content (%)			Zinc content (mg/kg)	Zinc uptake (g/ha)	Available soil nitrogen (kg/ha)	Available soil phosphorus (kg/ha)	Available soil potassium (kg/ha)
			25 DAS	50 DAS	At harvest					
FYM (t/ha)										
F_1	36.17	66.44	452.80	110.60	47.40	26.58	13.85	142.29	28.51	253.46
F_2	35.04	65.25	456.10	107.60	44.30	29.91	41.07	226.99	33.43	250.22
S.Em. ±	0.37	0.36	7.32	1.15	1.21	0.42	1.60	3.33	0.49	4.77
C.D. (*p*=0.05)	1.09	1.06	NS	NS	NS	29.91	4.71	9.77	1.43	NS
Zinc application										
Z_1	38.33	69.06	443.90	108.50	45.30	26.89	12.93	144.11	29.61	249.54
Z_2	34.63	66.22	463.30	107.60	44.40	28.18	16.17	189.09	31.24	257.91
Z_3	36.08	66.54	459.00	111.40	47.20	28.45	31.02	181.88	31.64	253.61
Z_4	36.13	66.90	448.60	109.80	47.80	28.38	23.14	162.84	30.80	256.10
Z_5	35.02	63.23	452.60	110.30	47.80	29.64	39.51	208.38	31.15	255.65
Z_6	33.43	63.15	459.30	108.10	42.60	27.93	41.99	221.53	31.38	238.23
S.Em. ±	0.64	0.62	12.68	2.00	2.10	0.73	2.78	5.77	0.84	8.26
C.D. (*p*=0.05)	1.90	1.83	NS	NS	NS	NS	8.15	16.92	NS	NS
Z × F	NS	Sig.	NS	NS	NS	NS	Sig.	Sig.	Sig.	NS
C.V. (%)	4.46	2.33	6.83	4.50	11.25	6.38	24.82	7.66	6.71	8.04

Note: ADF – Acid detergent fibre; NDF – Neutral detergent fibre; DAS – Days after sowing; HCN – Hydrocyanic acid; FYM – Farmyard manure; CD – Critical difference.

The effect of FYM on HCN content at 25 and 50 DAS and at harvest was non-significant and the Zn content and uptake in fodder sorghum as influenced by FYM application are presented in Table 4. Application of 10 t FYM/ha (F_2) resulted in higher Zn content (29.91 mg/kg) and uptake (41.07 g/ha) than the control (F_1: 0 t FYM/ha). The increased Zn uptake may be attributed to FYM application, which improves soil organic matter content, thereby enhancing cation exchange capacity and nutrient retention. These changes increase Zn availability in the soil, facilitating its uptake by plants (36). Farmyard manure supports a larger population of ZnSB such as *Bacillus*, *Pseudomonas* and *Rhizobium* species that release Zn from soil complexes, further increasing plant uptake.

Higher available N (226.99 kg/ha) and available P (33.43 kg/ha) were recorded in the F_2 (10 t FYM/ha) treatment compared with the control (F_1: 0 t FYM/ha). The effect of FYM application on available P after harvest was found to be non-significant (Table 4). The increase in available N content in the soil following FYM application may be attributed to enhanced N mineralisation and increased soil microbial activity, which facilitate the conversion of organically bound N into plant-available inorganic forms. The increase in available P after harvest might be attributed to FYM application, which releases organic acids during decomposition. These organic acids enhance the solubilisation and mobilisation of native P in the soil, thereby increasing P availability.

Data reported in Table 5 indicated that after harvest available soil Zn (mg/kg) was significantly affected by FYM application. Statistical analysis of the data presented in Table 5 showed that application of 10 t FYM/ha (F_2) resulted in significantly higher available Zn (2.96 mg/kg). Farmyard manure not only contributes to Zn directly but also supplies organic matter that binds Zn with humic and fulvic acids (39).

A higher ZnSB count in soil after harvest of fodder sorghum (1.7×10^6 cfu/g soil) was recorded with the 10 t FYM/ha (F_2) treatment compared with the F_1 (no manure) treatment (Table 5). Farmyard manure significantly boosts soil organic C, which serves as a vital energy source for soil microbes, including ZnSB. Farmyard manure fosters communities of ZnSB and fungi (*Bacillus* and *Pseudomonas*), which produce organic acids to release bound Zn from soil minerals (40).

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Table 5. Effect of farmyard manure and zinc on available soil zinc, Zn-solubilising bacteria count and economics

Treatments	Available soil zinc (mg/kg)	*ZnSB* count (*cfu*/g soil)		Total cost of cultivation (₹/ha)	Green fodder income (₹/ha)	Net income (₹/ha)	BCR
		Original value	Log-transformed value				
FYM (t/ha)							
F_1	2.33	1.9×10^3	4.31	40950	104800	63850	2.55
F_2	2.96	1.7×10^6	4.79	51500	168800	117300	3.27
S.Em. ±	0.06	15376	-	-	-	-	-
C.D.(*p*=0.05)	0.19	45098	-	-	-	-	-
Zinc application							
Z_1	2.57	3.7×10^3	3.56	40950	114800	73850	2.80
Z_2	2.45	3.7×10^3	3.56	42070	119600	77530	2.84
Z_3	2.95	4.2×10^3	3.61	43192	146800	103608	3.39
Z_4	2.31	2.9×10^6	6.22	42196	140000	97804	3.31
Z_5	2.75	2.3×10^4	4.12	46302	148400	102098	3.20
Z_6	2.84	2.9×10^6	6.23	46429	150400	103971	3.23
S.Em. ±	0.11	26633	-	-	-	-	-
C.D. (*p*=0.05)	0.33	78113	-	-	-	-	-
Z × F	Sig.	Sig.	-	-	-	-	-
C.V. (%)	10.53	6.69	-	-	-	-	-

Effect of zinc application

The data presented in Table 3 indicate that soil and foliar application of Zn significantly influenced plant height and the number of leaves per plant at harvest. Treatment Z_6, comprising the application of 12.5 kg Zn/ha through soil, followed by ZnSB soil application and 0.05 % Zn foliar spray, recorded significantly greater plant height (145.70 and 245.00 cm at 50 DAS and harvest respectively) and a higher number of leaves per plant (7.40 and 12.40 at 50 DAS and harvest respectively). The increase in plant height may be attributed to the role of Zn as an essential cofactor for enzymes involved in auxin synthesis, cell division and protein production, which promote stem elongation and overall vegetative growth (41–43). Similarly, the higher number of leaves per plant may be associated with improved Zn absorption through soil and foliar applications, which supports metabolic processes essential for leaf development. Zinc also contributes to auxin synthesis and chlorophyll production, thereby promoting plant growth and leaf development (44, 45).

Data reported in Table 3 indicated that treatment Z_5 (12.5 kg Zn/ha followed by 0.05 % Zn foliar application) reported a higher leaf-to-stem ratio (0.59). Adequate Zn supports leaf initiation and expansion more than stem elongation, leading to a higher leaf proportion (46).

Zinc application through soil and foliage had a significant effect on green fodder yield of fodder sorghum (Table 3). Application of 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application (Z_6) recorded significantly higher green fodder yield of fodder sorghum (376.33 q/ha). The minimum green fodder yield (287.17 q/ha) was recorded in treatment Z_1 (no application of Zn). The higher green fodder yield following both soil and foliar application of Zn might be due to the baseline supply of Zn in the root zone through soil application, while foliar spraying at key stages improves Zn concentration in plant tissues during critical growth stages, leading to optimal metabolic functioning and increased biomass (47). Zinc plays a crucial role in chlorophyll biosynthesis and enzyme functions linked to photosynthesis (45).

Fodder quality parameters such as dry matter content, dry matter yield, crude protein content and crude protein yield are responsible for better forage quality. Data presented in Table 3 revealed that application of 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application (Z_6) recorded higher dry matter content (31.47 %), dry matter yield (123.36 q/ha), crude protein content (8.76 %) and crude protein yield (11.59 q/ha). The lowest dry matter content (15.70 %) and minimum dry matter yield (46.75 q/ha), crude protein content (5.87 %) and crude protein yield (2.74 q/ha) were reported in treatment Z_1 (0 kg Zn/ha) compared with other treatments. Zinc acts as a cofactor in enzymes crucial for chlorophyll production, protein formation and carbon metabolism, resulting in greater accumulation of dry biomass (47). Improvement in crude protein content might be due to the application of Zn, as Zn acts as a cofactor for enzymes essential in N metabolism, including glutamate dehydrogenase, which promotes amino acid synthesis, ultimately increasing crude protein levels in fodder sorghum.

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Perusal of the data indicated a significant response of Zn application on ADF and NDF (Table 4). Application of 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application (Z_6) showed lower ADF (33.43 %) and NDF (63.15 %). Mean data regarding HCN content (Table 4) indicated a non-significant response at 25 and 50 DAS and at harvest.

Data presented in Table 4 revealed that Zn content and uptake by fodder sorghum were influenced by treatments. The response of Zn content in fodder sorghum to Zn application was non-significant, whereas Zn application had a significant effect on Zn uptake. Application of 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application (Z_6) recorded the highest zinc uptake (41.99 g/ha) by fodder sorghum.

After-harvest soil available N status was significantly affected by Zn application (Table 4). Perusal of the data indicated that application of 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application (Z_6) recorded higher available N (221.53 kg/ha), while the effects of Zn application on available P and K were non-significant (Table 4). The higher available N content in the soil after harvest may be attributed to the role of Zn as an essential cofactor for enzymes involved in N assimilation and protein synthesis. Adequate Zn application may improve plant N uptake and utilisation, thereby influencing the residual N content in the soil after harvest (48). Zinc and phosphorus exhibit an antagonistic interaction; increased P levels can reduce Zn availability to plants (47).

Statistically analysed mean data indicated that Zn application has a significant effect on available soil Zn content after harvest (Table 5). Higher after-harvest available soil Zn status (2.95 mg/kg) was recorded with treatment Z_3 (25 kg Zn/ha).

Perusal of the mean data presented in Table 5 indicated that the higher microbial count in the soil after harvest of fodder sorghum (2.9×10^6 cfu/g soil) was recorded with treatment Z_6 (12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application). Zinc fertilisation increases the pool of available Zn, which acts as both a micronutrient and a stimulant for ZnSB growth. Zinc solubilising bacteria produce organic acids and siderophores that solubilise bound Zn, creating a feedback loop that further supports microbial proliferation. Foliar application may indirectly enhance microbial dynamics by improving plant health and root exudation, which provides more substrates for microbial growth (40).

Interaction effect

Statistically analysed mean data presented in Table 3 revealed that the interaction effect of FYM × Zn application on periodical plant height, number of leaves per plant at 25 and 50 DAS and at harvest and green fodder yield of fodder sorghum was non-significant.

Data presented in Table 6 indicated that the combination F_2Z_6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) recorded the highest leaf-stem ratio (0.74). Farmyard manure provides sustained organic nutrient release, while the soil + foliar zinc application ensures both baseline and timely micronutrient availability. Together, these enhance leaf initiation, expansion and retention more than stem growth, thereby increasing the leaf-to-stem proportion (49). Under adequate Zn conditions, plants tend to allocate more biomass to structural tissues, which are rich in cellulose, hemicellulose and lignin, thereby resulting in higher fibre content (50). When Zn is also applied, it supports enzymatic functions in microbes and plants that optimise N transformations, leading to higher post harvest available N in soil (51).

Data presented in Tables 7, 8 and 9 revealed that treatment combination F_2Z_5 (10 t FYM/ha × 12.5 kg Zn/ha fb 0.05 % Zn foliar application) recorded higher dry matter content (39.00 %), dry matter yield (180.73 q/ha) and crude protein yield (18.61 q/ha). The application of FYM and zinc enhances chlorophyll synthesis, enzymatic activity and photosynthesis. This leads to increased plant height, leaf area and dry matter accumulation (52).

Data presented in Table 10 indicated that treatment combination F_2Z_6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) recorded the highest crude protein content (10.68 %). Zinc acts as a vital cofactor for enzymes involved in N assimilation and amino acid synthesis. Coupled with the organic N released from FYM decomposition, it enhances crude protein accumulation in sorghum tissues (48). Crude protein yield of fodder sorghum was higher under combined application of FYM and Zn, which might be due to adequate supply of all essential micro- and macro-nutrients through FYM and Zn, allowing the plant to build more protein. The optimal nutrient environment created by FYM and Zn fosters robust chlorophyll production and photosynthetic rates, generating more substrates for protein biosynthesis in vegetative tissues (49).

Perusal of the data presented in Table 4 indicated that the interaction effect of FYM × Zn application with respect to ADF content at 25, 50 and at harvest, HCN content, Zn content and available soil K after harvest was non-significant.

Data presented in Table 11 indicated that treatment combination F_2Z_6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) reported the lowest neutral detergent fibre (62.64 %). Mean interaction data presented in Tables 12 and 13 revealed that treatment combination F_2Z_6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) showed higher Zn uptake (64.03 g/ha) and available N in soil (277.53 kg/ha) than other treatments except treatment F_2Z_5. The higher available N content in the soil after harvest might be attributed to the

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application of FYM, which enriches soil organic matter, enhances microbial activity and improves nutrient retention and mineralisation, thereby increasing N availability. Treatment combination F_2Z_3 (10 t FYM/ha × 25kg Zn/ha) showed higher available P in soil (36.98 kg/ha) than the rest of the treatments except treatment F_2Z_2 (Table 14). As microbes decompose FYM, they release organic acids (humic and carboxylic acids) that chelate soil-bound phosphorus and convert it into plant-available forms. Zinc mostly influences enzyme systems and plant physiology, not the release of soil phosphorus (51).

Table 6. Interaction effect on leaf-stem ratio of fodder sorghum

FYM (t/ha)	Leaf-stem ratio					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	0.38	0.43	0.47	0.46	0.53	0.42
F2	0.33	0.43	0.46	0.56	0.65	0.74
S.Em. ±	0.037					
C.D. (*p*=0.05)	0.108					

Note: ZnSB: Zinc-solubilising bacteria; FYM : farmyard manure; CD: Critical difference.

Table 7. Interaction effect of FYM and zinc on dry matter content

FYM (t/ha)	Dry matter content (%)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	13.57	16.30	27.47	28.13	23.73	26.50
F2	17.83	20.53	33.87	31.77	39.00	36.43
S.Em. ±	1.13					
C.D. (*p*=0.05)	3.33					

Note: ZnSB: Zinc-solubilising bacteria; FYM:farmyard manure; CD: Critical difference.

Table 8. Interaction effect of FYM and zinc on dry matter yield

FYM (t/ha)	Dry matter yield (q/ha)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	29.36	36.57	76.62	81.38	64.60	75.94
F2	64.15	75.91	152.40	129.59	180.73	170.79
S.Em. ±	8.89					
C.D. (*p*=0.05)	26.09					

Note: ZnSB: Zinc-solubilising bacteria; FYM : farmyard manure; CD: Critical difference.

Table 9. Interaction effect of FYM and zinc on crude protein yield

FYM (t/ha)	Crude protein yield (q/ha)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	1.67	2.15	5.17	5.82	4.35	5.18
F2	3.81	5.82	14.48	10.93	18.61	18.00
S.Em. ±	0.92					
C.D. (*p*=0.05)	2.71					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

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Table 10. Interaction effect of FYM and zinc on crude protein content

FYM (t/ha)	Crude protein content (%)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	5.71	5.90	6.80	7.15	6.74	6.83
F2	6.02	7.66	9.51	8.44	10.24	10.68
S.Em. ±	0.39					
C.D. (p=0.05)	1.14					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

Table 11. Interaction effect of FYM and zinc on neutral detergent fibre content

FYM (t/ha)	Neutral detergent fiber (%)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	68.45	68.99	68.02	67.58	62.97	63.65
F2	69.66	63.46	65.07	66.22	63.50	62.64
S.Em. ±	0.88					
C.D. (p=0.05)	2.60					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

Table 12. Interaction effect of FYM and zinc on zinc uptake

FYM (t/ha)	Zinc uptake (g/ha)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	7.40	9.64	15.02	12.91	18.15	19.94
F2	18.45	22.70	47.02	33.37	60.87	64.03
S.Em. ±	3.93					
C.D. (p=0.05)	11.53					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

Table 13. Interaction effect of FYM and zinc on available soil nitrogen after harvest of fodder sorghum

FYM (t/ha)	Available soil nitrogen (kg/ha)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	118.18	144.59	143.21	130.66	151.57	165.53
F2	170.03	233.59	220.56	195.02	265.19	277.53
S.Em. ±	8.16					
C.D. (p=0.05)	23.93					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

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Table 14. Interaction effect of FYM and zinc on available soil phosphorus after harvest of fodder sorghum

FYM (t/ha)	Available soil phosphorus (kg/ha)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	27.95	27.65	26.30	29.18	30.23	29.74
F2	31.28	34.82	36.98	32.41	32.06	33.03
S.Em. ±	1.20					
C.D.(p=0.05)	3.51					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

The treatment combination F2Z6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) showed higher available soil Zn (3.40 mg/kg) compared to the rest of the treatments (Table 15) except treatments F2Z5 and F2Z3. The significant increase in available Zn reflects the additive effect of Zn supplied directly by FYM, enhanced retention and reduced soil adsorption due to elevated organic matter (52). A significantly higher microbial count in soil after harvesting (Table 16) of fodder sorghum (5.2 × 106 cfu/g soil) was found with treatment combination F2Z6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) and F2Z6 (10 t FYM/ha × 12.5 kg Zn/ha followed by ZnSB soil application).

Economics

Economics of the experiment were tabulated in Table 5. The application of 10 t FYM/ha (F2) to fodder sorghum resulted in the highest green fodder income (₹ 168800/ha), net income (₹ 117300/ha) and benefit-cost ratio (3.27).

Data illustrated in Table 5 revealed that Zn application treatment Z6 (12.5kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application) to fodder sorghum resulted in maximum green fodder income (₹ 150400/ha) and net income (₹ 103971/ha), with a benefit-cost ratio of 3.2.

4. Conclusion

Based on the findings of the field experiment, it can be concluded that application of 10 t FYM/ha significantly enhanced green fodder yield of fodder sorghum. This treatment performed better in terms of dry matter yield, crude protein yield and net returns per hectare. Application of 12.5 kg Zn/ha followed by ZnSB soil application followed by 0.05 % Zn foliar application resulted in higher plant height, number of leaves per plant at harvest, leaf-to-stem ratio, green fodder yield, proximate analysis like dry matter, crude protein, acid detergent fibre, neutral detergent fibre, as well as zinc uptake and improved soil nutrient status. The treatment combination F2Z5 (10 t FYM/ha + 12.5 kg Zn/ha followed by 0.05 % Zn foliar application) recorded higher dry matter yield and crude protein yield.

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Table 15. Interaction effect of FYM and zinc on available soil Zn after harvest of fodder sorghum

FYM (t/ha)	Available soil Zn (mg/kg)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	2.22	2.34	2.67	2.20	2.26	2.28
F2	2.91	2.56	3.24	2.43	3.24	3.40
S.Em. ±	0.16					
C.D. (p=0.05)	0.47					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

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Table 16. Interaction effect of FYM and zinc on *ZnSB* count after harvest of fodder sorghum

FYM (t/ha)	ZnSB count (cfu/g soil)					
	Zinc application					
	Z1	Z2	Z3	Z4	Z5	Z6
F1	3.2×10^3 (3.50)	3.7×10^3 (3.56)	5.7×10^3 (3.71)	5.6×10^5 (5.74)	4.1×10^3 (3.61)	5.6×10^5 (5.74)
F2	4.3×10^3 (3.63)	3.7×10^3 (3.56)	3.3×10^3 (3.52)	5.2×10^6 (6.71)	4.3×10^4 (4.63)	5.2×10^6 (6.71)
S.Em. ±	37665					
C.D. (p=0.05)	110469					

Note: ZnSB: Zinc-solubilising bacteria; FYM: farmyard manure; CD: Critical difference.

Authors' contributions

AT conducted the experiment and collected all primary data. HKP analysed all primary data, interpreted the results and prepared and finalised the manuscript. PHR conducted the biochemical analysis of all quality parameters. CHR contributed to the correction and improvement of the research text. CK and ADP assisted in collecting all observations during the experimental period. All authors read and approved 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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