

IMPACT OF FOLIAR ZINC BIOFORTIFICATION ON SORGHUM FODDER: A STRATEGY FOR IMPROVED LIVESTOCK NUTRITION

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Abstract

Sorghum (*Sorghum bicolor* L.), a critical dual-purpose crop, faces micronutrient limitations that undermine its viability as livestock feed. Zinc deficiency is pronounced in sorghum-based feed. Hence, to increase the zinc contents of sorghum fodder, the present study investigated zinc sulphate foliar application (0, 0.5, 1.0%) across four cultivars (Sorghum-263, JS-2002, Hegari, Sorghum-2011). The experiment was conducted at the University of Agriculture, Faisalabad, Pakistan, using a completely randomized design (factorial) with three replications. Results depicted that the 0.5% zinc treatment consistently outperformed other concentrations, irrespective of cultivar. Agronomically, it maximizes plant height (+18% vs. control), leaf production (+24%), and fodder yield (green and dry matter by 31% and 28%, respectively), alongside boosting chlorophyll synthesis. Nutritionally, it elevated crude protein (10.75% vs. 8.2% in control) and zinc concentration (153.13 vs. 89.4 mg kg⁻¹) while reducing fiber fractions (26.03% fiber, 61.91% NDF, 32.18% ADF), enhancing overall digestibility. These results establish 0.5% zinc sulphate as a cost-effective foliar strategy to concurrently elevate sorghum's biomass productivity and nutritional value, addressing micronutrient gaps in livestock diets. The study promotes targeted zinc management to fortify fodder systems against nutrient deficiencies in livestock.

INTRODUCTION

Pakistan's agriculture sector remains a cornerstone of its economy and a primary source of rural employment. According to the Pakistan Bureau of Statistics (2025), the sector contributes 23.54% to the national GDP and employs more than 37% of the country's labor force. In Fiscal Year 2025, the sector grew by 0.56%, a performance largely driven by a strong 4.72%

expansion in the livestock subsector, which itself accounts for a significant 14.97% share of the gross domestic product (GDP) (GOP., 2025). However, a critical challenge is emerging, while the livestock population is growing steadily at 2.70% per year, the cultivation area for vital Kharif season sorghum fodder has decreased by 2.14% (Ministry of National Food Security &

Research, 2025). This declining fodder supply creates a major problem for sustaining this growth. During shortage periods, the quality of available fodder becomes critically important. It is essential to ensure animals receive complete nutrition to maintain health and productivity, making quality management not just beneficial, but a necessity for the sector's resilience.

Among staple crops, sorghum (*Sorghum bicolor* L.), a C4 grass renowned for its drought resilience and adaptability to marginal soils, stands out as a vital dual-purpose crop in arid and semi-arid regions (Ayub et al., 2004; Schittenhelm and Schroetter, 2014). Beside human consumption, sorghum emerges as a strategic forage resource in ruminant production systems, particularly in arid and semi-arid regions where soil constraints and water scarcity limit conventional fodder crops (Iqbal and Iqbal, 2015; Mabelebele et al., 2015).

Despite its agronomic advantages, sorghum's nutritional profile often lacks essential micronutrients such as zinc, calcium, and iron, compromising its utility in livestock feed systems (Chattha et al., 2017; Abdelhalim et al., 2019). This deficiency has cascading implications such as, inadequate zinc in fodder correlates with stunted growth, impaired immunity, and decreased milk productivity in cattle, while indirect dietary zinc gaps exacerbate malnutrition in human populations reliant on dairy products (Capstaff and Miller, 2018; Szerement et al., 2022). Zinc, a cofactor for over 300 enzymatic processes in plants, is indispensable for protein synthesis, auxin regulation, and metabolic activities underpinning crop productivity (Shukla et al., 2015; Zhang et al., 2021). However, nearly 30% of global croplands including Pakistan's calcareous soils, exhibit zinc deficiency, leading to suboptimal yields and nutrient-depleted harvests (Hafeez et al., 2013; Ohly et al., 2019).

Biofortification via micronutrient fertilization offers a scalable solution to enrich fodder crops,

thereby enhancing mineral transfer through the livestock-to-human food chain (Bansode and Kumar, 2015). While soil zinc application is common, foliar supplementation demonstrates higher efficacy in overcoming soil pH limitations for nutrient uptake (Hosnedlova et al., 2007). While zinc is essential for plant metabolism, the lack of field-based data on sorghum's cultivar-specific zinc thresholds and cost-effective application rates hinders biofortification efforts. To address this critical gap the present study hypothesized that foliar zinc sulfate application enhances both agronomic productivity and nutritional quality in diverse sorghum cultivars while maintaining yield stability under resource-limited farming systems.

Materials and methods

Plant material, site description, and soil preparation

This study evaluated the growth response of four sorghum (*Sorghum bicolor* L.) genotypes—Sorghum-263, JS-2002, Hegari, and Sorghum-2011—to foliar applications of three zinc sulphate concentrations (0%, 0.5%, and 1%) with the sowing operation completed on May 10, 2023. While eight plants were initially established per pot, only four uniform plants were selectively maintained to ensure consistent data collection for all analyses.

Prior to sowing, composite soil samples (0–30 cm depth) were collected from the experimental site to assess physicochemical properties, including texture, pH, organic matter content, and macro-/micronutrient availability (Association of Official Analytical Chemists (AOAC), 2023) (Table 1). The soil was homogenized and sieved through a 2-mm mesh to ensure uniformity before filling pots.

Table 1. Physiochemical characteristics of experimental soil

Texture	Phosphorus mg kg ⁻¹	Potassium mg kg ⁻¹	Nitrogen (N) mg kg ⁻¹	Electrical conductivity (dSm ⁻¹)	Organic matter (%)	pH	Saturation (%)
Loam	32.5	162	24.9	1.09	1.61	8.2	36

Data Collection

The study assessed agronomic, physiological, and quality parameters in sorghum, including morphological traits (leaf count, plant height, fresh and dry forage yield) and physiological attributes (chlorophyll content). Leaf number was recorded at 60 days after sowing (DAS) by averaging counts from two randomly selected plants per pot. Plant height (cm) was measured from the soil base to the flag leaf tip. Fresh forage yield (g/plant) was determined immediately after harvest, while dry yield was obtained after oven-drying samples at 65°C. Chlorophyll content (mg/m²) was measured non-destructively using a SPAD-502 meter. All data were collected in replicates to ensure reliability.

Proximate analysis

Proximate analysis was conducted at the Animal Husbandry Laboratory, Institute of Animal and Dairy Sciences, University of Agriculture Faisalabad, Pakistan following the standard methods of AOAC (2006). The analysis included determinations of crude protein, extract, crude fiber, ash content, neutral detergent fiber (NDF), acid detergent fiber (ADF), and zinc content to evaluate the nutritional composition of sorghum samples.

Crude protein (%) was determined using the Kjeldahl method. Briefly, 1 g of oven-dried sample was digested with 30 mL of concentrated sulfuric acid (H₂SO₄) and 5 g of a digestion mixture (K₂SO₄ + CuSO₄·5H₂O and FeSO₄) in a Kjeldahl flask. The digested sample was diluted to 250 mL with distilled water, and 10 mL of this solution was subjected to steam distillation in the presence of 40% NaOH. The liberated ammonia (NH₃) was trapped in 4% boric acid solution containing methyl red indicator. The ammonia-boric acid complex was then titrated against 0.1N H₂SO₄ until a light pink endpoint was reached.

The volume of acid consumed was used to calculate nitrogen content, which was converted to crude protein by multiplying by a factor of 6.25.

$$Nitrogen\% = \frac{0.1 \text{ ml } NH_2SO_4 \times 0.00014 \times 250}{Weight\ of\ sample \times volume\ of\ diluted\ sample}$$

Eq.1

The following formula was used to find out crude protein;

$$Crude\ protein\ (\%) = Nitrogen\ (\%) \times 6.25$$

Eq.2

Ether extract (EE) (%), representing the fat content, was determined using Soxhlet extraction. A 2g oven-dried sample was placed in an extraction thimble and subjected to continuous extraction with diethyl ether for 6-8 hours. The extracted fat was collected in a pre-weighed flask, and the solvent was evaporated at 70°C. The remaining residue was weighed to determine the extractable fat content.

$$W_3 = W_1 - W_2 = Weight\ of\ pure\ fat$$

Eq.3

Where, W₁ = weight of the empty petri dish, W₂ = weight of beaker - fat from 2.0 g sample of dried plant material fat percentage was calculated according to (AOAC, 2006).

$$EE\% = \frac{Wt.\ of\ residue}{Wt.\ of\ sample} \times 100$$

Eq.4

Crude fiber (CF) (%) was analyzed by sequential acid and alkaline digestion. A 2 g defatted sample was boiled in 200 mL of 1.25% H₂SO₄ for 30 minutes, filtered, and washed with distilled water.

The residue was then boiled in 200 mL of 1.25% NaOH for another 30 minutes, filtered, and washed again. The remaining residue was dried at 105°C to a constant weight and then ashed in a muffle furnace at 600°C. The loss in weight upon ashing represented the crude fiber content.

$$CF\% = \frac{\text{Weight of dried residues} - \text{weight of ash}}{\text{Weight of sample}} \times 100 \quad \text{Eq.5}$$

Ash content (%) was determined by incinerating 5 g of oven-dried sample in a pre-weighed crucible at 600°C in a muffle furnace until white or gray ash was obtained. The crucible was cooled in a desiccator and weighed, and the ash content was calculated as the percentage of the residue relative to the original sample weight.

$$Ash\% = \frac{\text{Wt.of Ash}}{\text{Wt.of sample}} \times 100 \quad \text{Eq.6}$$

Neutral detergent fiber (NDF, %) was analyzed by refluxing 2 g of sample in a neutral detergent solution (containing sodium lauryl sulfate, disodium EDTA, sodium tetraborate, and ethoxyethanol, pH 6.9–7.0) for 60 minutes. The residue was filtered, washed with hot water, dried at 100°C, and weighed. NDF was calculated as the percentage of dried residue relative to the sample weight.

$$NDF\% = \frac{(\text{Crucible wt+residues})-(\text{Crucible wt})}{\text{Weight of sample}} \times 100 \quad \text{Eq.7}$$

Acid detergent fiber (ADF, %) was determined similarly, using an acid detergent solution (20 g cetyltrimethylammonium bromide in 1N H₂SO₄). The sample was refluxed for 30 minutes, filtered, washed, dried, and weighed. ADF was calculated as the percentage of the dried residue relative to the sample weight.

$$ADF\% = \frac{(\text{residues+Crucible wt})-(\text{Crucible wt})}{\text{Weight of sample}} \times 100 \quad \text{Eq.8}$$

Zinc content (mg kg⁻¹) was measured by digesting 1 g of powdered sample in a mixture of nitric

acid (HNO₃) and perchloric acid (HClO₄) (10:5 mL) at 235°C until a clear digest was obtained. The digest was diluted, and zinc concentration was quantified using atomic absorption spectrophotometry. The zinc content was calculated based on the concentration, digest volume, and sample weight.

$$\text{Zinc (ppm)} = \frac{\text{ppm Zn} \times \text{total volume of plant digest (ml)}}{\text{weight of dry plant (g)}} \quad \text{Eq. 9}$$

This comprehensive analysis provided detailed insights into the nutritional and compositional properties of the sorghum samples, ensuring accurate and reliable data for further research and application.

Statistical analysis

The experimental data were analyzed using Python (version 3.9) with the SciPy (version 1.7.3) and statsmodels (version 0.13.2) libraries. Analysis of variance (ANOVA) was performed to determine significant differences among treatment groups, followed by post-hoc pairwise comparisons using Tukey's Honestly Significant Difference (HSD) test at a 95% confidence level ($\alpha = 0.05$). All statistical procedures were using the Jupyter Notebook environment, with results visualized using matplotlib (version 3.5.1) and seaborn (version 0.11.2) libraries.

Results

Plant height (cm)

In the present study, we evaluated the influence of zinc (Zn) fertilization and varietal selection on sorghum plant height through rigorous statistical analysis. Analysis of variance revealed significant effects ($P < 0.05$) of zinc application rates on plant height, with 0.5% ZnSO₄ treatment producing the maximum mean height of 152.08 cm. This optimal concentration enhanced vertical growth, while the higher 1% ZnSO₄ application resulted in significantly reduced plant height (123.41 cm), likely due to zinc toxicity effects that inhibited normal plant development.

Interestingly, our results demonstrated no statistically significant differences ($P > 0.05$) in plant height among the four sorghum varieties examined, suggesting that genetic differences between these cultivars did not substantially influence this growth parameter under the experimental conditions. Furthermore, the interaction between zinc levels and sorghum varieties was found to be non-significant,

indicating that the response to zinc fertilization was consistent across all tested genotypes. These findings collectively suggest that while zinc nutrition plays a crucial role in determining sorghum plant height, with both deficiency and excess being detrimental, the effect is largely independent of varietal differences among the genotypes studied.

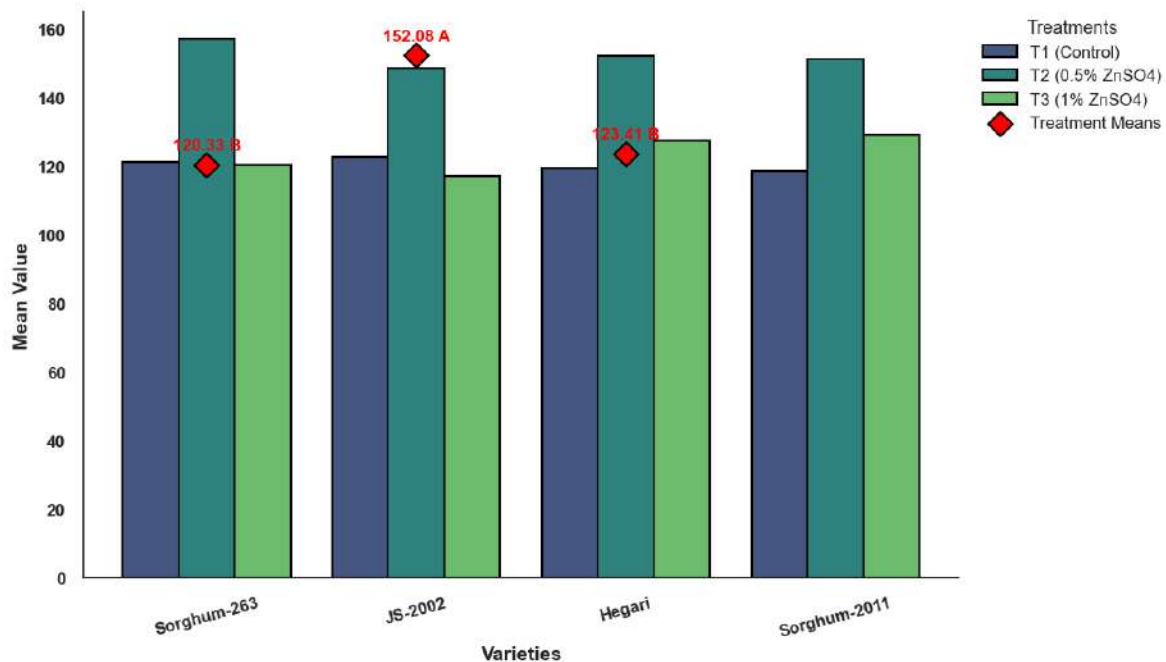


Figure 1. Effect of zinc concentrations on the plant height (cm) of sorghum genotypes. Bars for each genotype with different letters are significantly different from each other according to Tukey's Honest Significant Difference (HSD) test at $*p \leq 0.05$. Error bars represent the standard error of the mean.

Number of leaves/plants

Statistical analysis revealed significant zinc effects on leaf number in sorghum ($P < 0.05$). The 0.5% $ZnSO_4$ treatment produced the highest leaf count (12.00), while the 1% application reduced leaf number (9.33), indicating toxicity effects at elevated concentrations. These results demonstrate the importance of optimal zinc

dosage for promoting foliar development in sorghum. No significant varietal differences were observed among the four sorghum genotypes tested ($P > 0.05$), with all varieties showing comparable leaf production. Furthermore, the non-significant zinc \times variety interaction confirmed consistent responses across cultivars, with no specific variety showing enhanced zinc sensitivity. These findings suggest that while zinc nutrition has a critical influences leaf development in sorghum, it's effect remains uniform across different genetic backgrounds. The results emphasize the need for precise zinc management, with 0.5% $ZnSO_4$ emerging as the optimal concentration for maximizing leaf production.

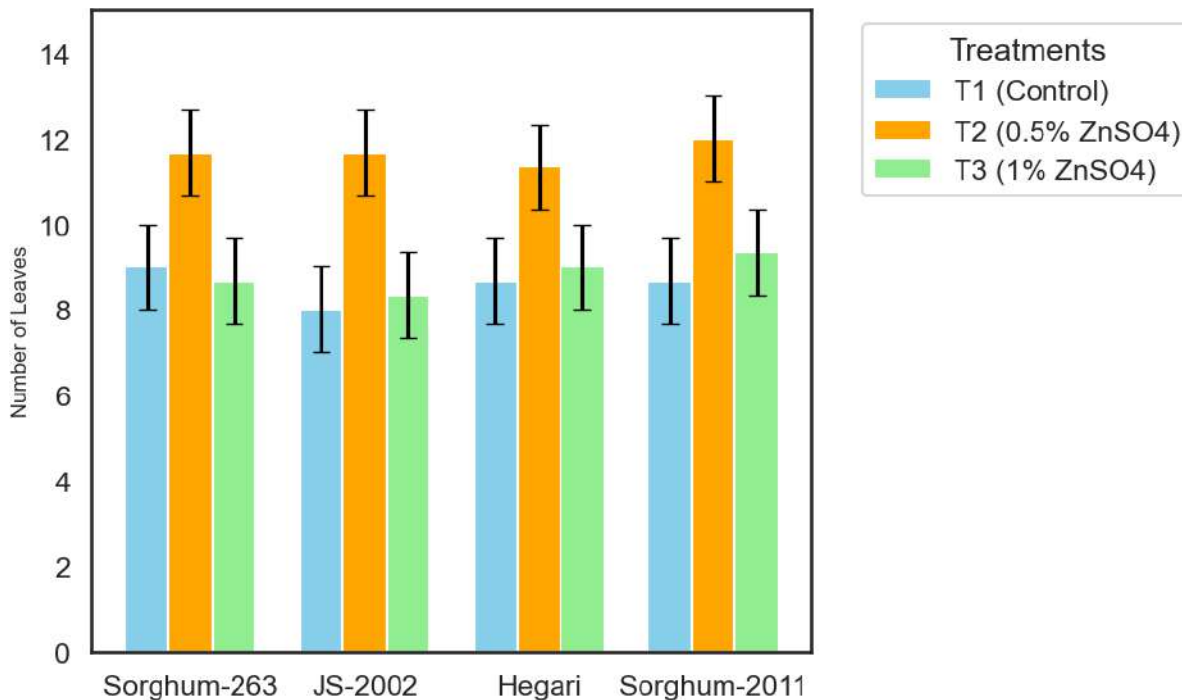


Figure 2. Effect of zinc concentrations on the number of leaves of sorghum genotypes. Bars for each genotype with different letters are significantly different from each other according to Tukey's Honest Significant Difference (HSD) test at $*p \leq 0.05$. Error bars represent the standard error of the mean.

Green and dry fodder yield (t/ha)

The analysis of zinc application effects on sorghum yield revealed significant findings for both green fodder and dry matter production. For green fodder yield measured at 60 days after sowing, ANOVA showed a significant response to zinc levels ($P < 0.05$), with the 0.5% ZnSO₄ treatment producing the highest yield (254.58 g/plant). In contrast, the 1% ZnSO₄ application resulted in a significantly lower yield (167.91 g/plant), suggesting zinc toxicity at higher concentrations. No significant varietal differences were observed among the four sorghum genotypes ($P > 0.05$), indicating consistent yield

potential across varieties. The zinc \times variety interaction was non-significant, demonstrating uniform responses to zinc application regardless of cultivar.

Similar patterns emerged for dry matter yield, where the 0.5% ZnSO₄ treatment again showed superior performance (52.50 g/plant), significantly higher ($P < 0.05$) than both the control and 1% ZnSO₄ treatment (38.50 g/plant). As with green fodder yield, no significant varietal differences ($P > 0.05$) or zinc \times variety interactions were detected for dry matter production. These consistent results across both yield parameters demonstrate that while zinc nutrition significantly influences sorghum productivity, with 0.5% ZnSO₄ being clearly optimal, genetic differences between the tested varieties had minimal impact on yield responses under the experimental conditions. The findings emphasize the importance of precise zinc management in sorghum cultivation while suggesting the broad applicability of these zinc recommendations across different varieties.

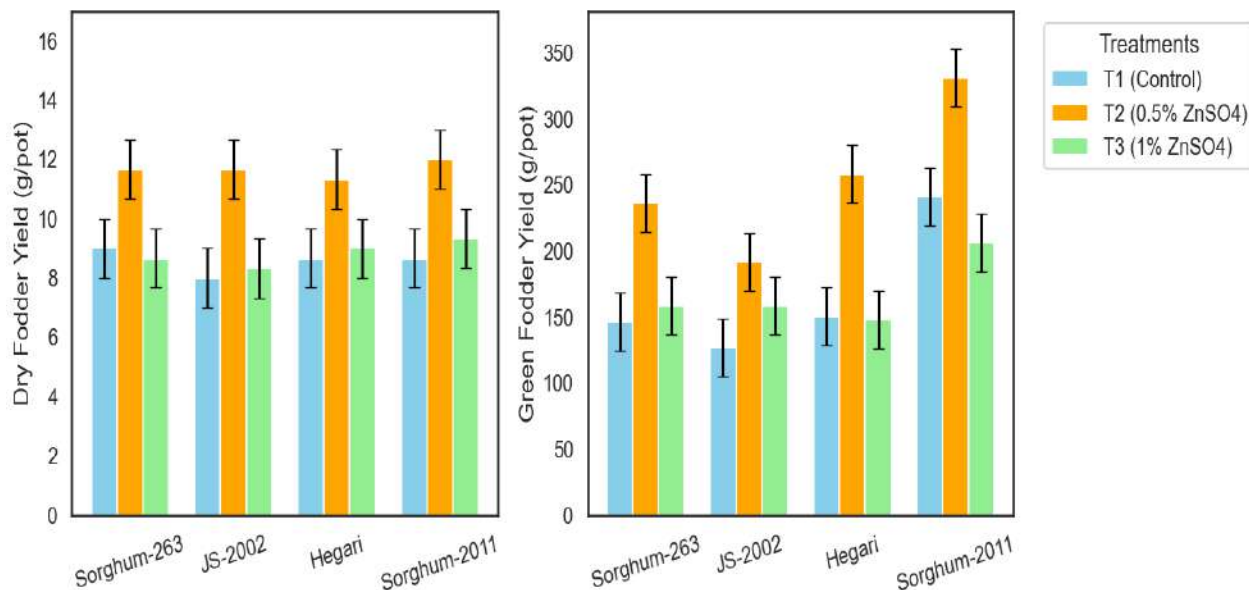


Figure 3. Effect of zinc concentration on green fodder yield and dry fodder yield (t/ha) of sorghum genotypes. Bars for each genotype with different letters are significantly different from each other according to Tukey's Honest Significant Difference (HSD) test at $*p \leq 0.05$. Error bars represent the standard error of the mean.

Protein%, Ether extract%, Fiber%

The study revealed significant impacts of zinc fertilization on key nutritional parameters of sorghum. Zinc application at 0.5% ZnSO₄ concentration consistently demonstrated optimal results, increasing crude protein content by 21.5% (10.75% vs 9.29% at 1% ZnSO₄) and crude fat content by 26.9% (3.91% vs 3.08% at 1% ZnSO₄), while simultaneously reducing crude fiber content by 17.4% (26.03% vs 31.50% at 1% ZnSO₄). These findings suggest that moderate zinc supplementation enhances sorghum's nutritional value by promoting protein and fat synthesis while improving digestibility through fiber reduction. Notably, the response patterns were consistent across all four sorghum varieties tested, as evidenced by non-significant varietal

differences ($P > 0.05$) and absence of zinc × variety interactions. The uniform response indicates that genetic differences among the tested cultivars did not substantially influence the nutritional responses to zinc application under the experimental conditions.

The 1% ZnSO₄ treatment consistently showed detrimental effects across all measured parameters, likely due to zinc toxicity. This was particularly evident in protein and fat content reductions, coupled with increased fiber content, suggesting impaired metabolic processes at higher zinc concentrations. These results have important practical implications for sorghum cultivation. The 0.5% ZnSO₄ application emerges as an effective strategy to simultaneously enhance multiple nutritional quality parameters in sorghum, regardless of varietal selection. The findings are particularly relevant for improving sorghum's value as both human food and livestock feed, where balanced protein, fat, and fiber contents are crucial for nutritional quality and digestibility. The consistent responses across varieties simplify zinc management recommendations, suggesting the broad applicability of these findings across different sorghum genotypes.

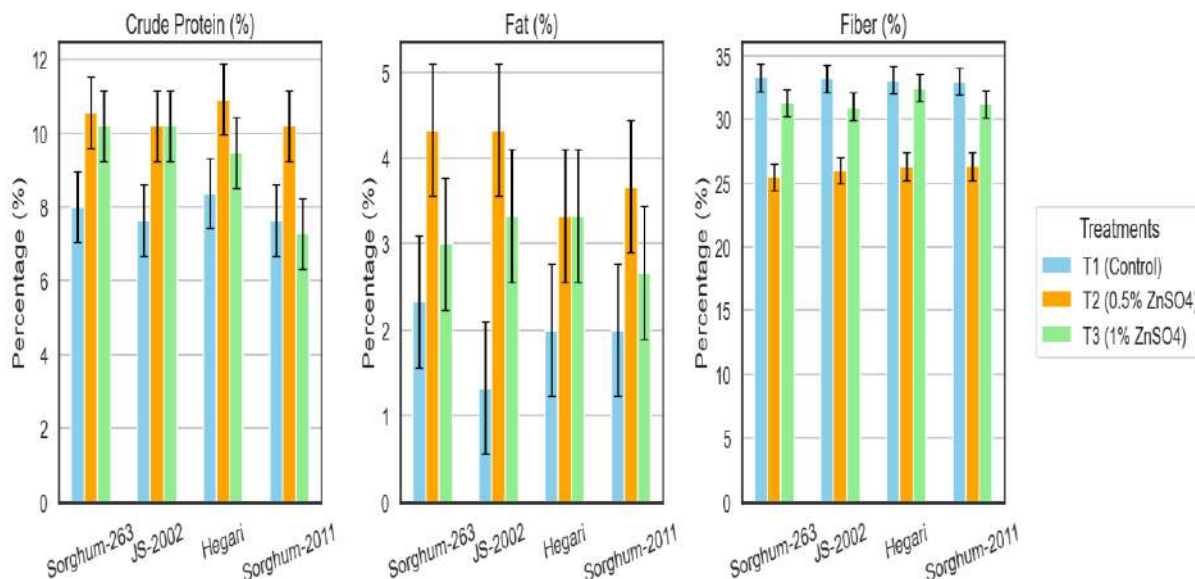


Figure 4. Effect of zinc concentration on (4A, fat%), (4B, fiber%) and (4C, protein%) of sorghum genotypes. Bars for each genotype with different letters are significantly different from each other according to Tukey's Honest Significant Difference (HSD) test at $p \leq 0.05$. Error bars represent the standard error of the mean.

NDF and ADF%

The study investigated the impact of zinc fertilization on neutral detergent fiber (NDF) and acid detergent fiber (ADF) content in sorghum, important parameters determining forage quality. Zinc application significantly influenced both fiber fractions ($P < 0.05$), with 0.5% ZnSO₄ demonstrating optimal effects by reducing NDF to 61.91% (vs 75.95% in control/1% ZnSO₄) and ADF to 32.18% (vs 38.87% in control/1%

ZnSO₄). These reductions indicate improved digestibility potential, as lower fiber content typically correlates with enhanced feed quality and rumen digestibility in livestock. Notably, the 1% ZnSO₄ treatment showed elevated fiber levels comparable to the control, suggesting zinc toxicity impairs normal plant development and increases lignification. The consistent fiber reduction at 0.5% ZnSO₄ across both NDF (18.4%) and ADF (17.2%) measurements demonstrates this concentration's effectiveness in optimizing sorghum's structural composition. Genetic factors showed minimal influence, as no significant varietal differences ($P > 0.05$) were observed for either NDF or ADF content among the four sorghum genotypes tested. Furthermore, the non-significant zinc × variety interactions confirmed uniform responses to zinc application across all varieties, indicating that the beneficial effects of 0.5% ZnSO₄ on fiber characteristics are genotype independent.

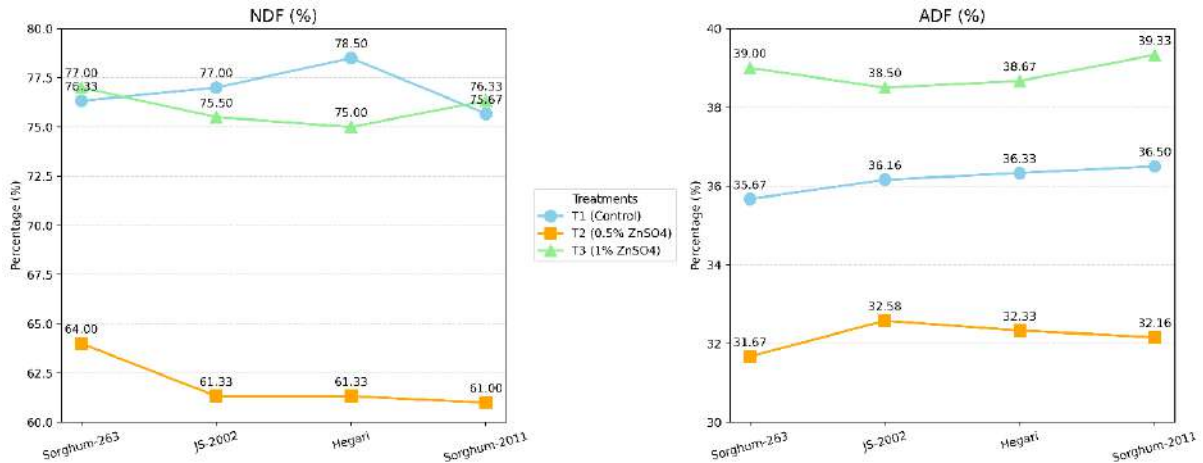


Figure 5. Effect of zinc concentration on NDF and ADF%, of sorghum genotypes. Chlorophyll content (mg/m²)

Chlorophyll, the primary photosynthetic pigment in plants, plays a crucial role in light absorption (particularly in blue and red wavelengths) and energy conversion, directly influencing plant productivity and fodder quality. As chlorophyll content correlates with photosynthetic efficiency, it serves as a key indicator of plant health and potential for biomass production. Statistical analysis revealed a significant effect ($P < 0.05$) of zinc application on chlorophyll content. The 0.5% ZnSO₄ treatment yielded the highest chlorophyll concentration (51.17 mg/m²), demonstrating zinc's role in enhancing photosynthetic capacity. In contrast, the 1% ZnSO₄ application resulted in significantly reduced chlorophyll content (40.06 mg/m²),

likely due to zinc toxicity impairing pigment synthesis. No significant varietal differences ($P > 0.05$) were observed among the sorghum genotypes, indicating consistent chlorophyll production across cultivars. Furthermore, the non-significant zinc × variety interaction ($P > 0.05$) confirmed that zinc's effect on chlorophyll content was uniform regardless of genetic background. These findings suggest that while optimal zinc fertilization (0.5% ZnSO₄) significantly boosts photosynthetic potential in sorghum, varietal selection has minimal impact on chlorophyll-related responses under the tested conditions.

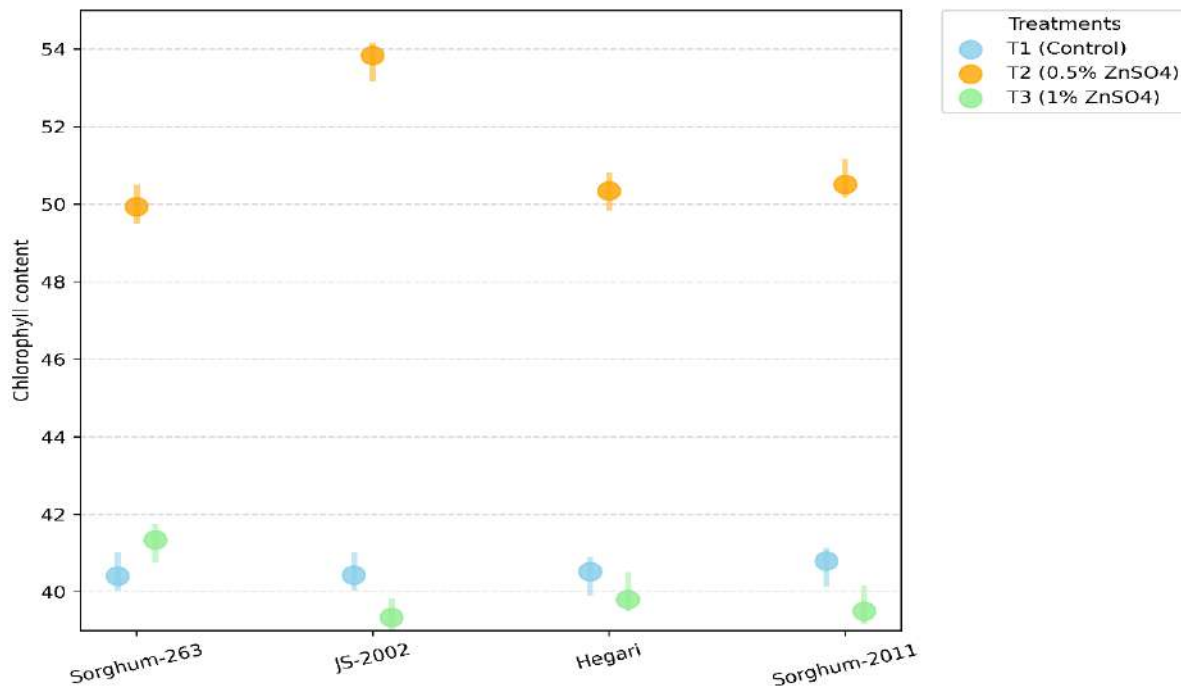


Figure 6. Effect of zinc concentration on chlorophyll content (mg/m²) of sorghum genotypes.

Zinc content (mg kg⁻¹)

Zinc, a crucial micronutrient for plant growth and development, plays vital roles in enzyme activation, protein synthesis, and hormone regulation. As a component of superoxide dismutase (SOD), zinc contributes to cellular protection against oxidative damage, influencing overall plant health and longevity. The study revealed significant effects of zinc fertilization on sorghum zinc content ($P < 0.05$). While the 1% ZnSO₄ treatment resulted in maximum zinc accumulation (272.37 mg kg⁻¹), this

concentration induced toxicity symptoms. In contrast, the 0.5% ZnSO₄ application showed optimal zinc content (153.13 mg kg⁻¹) without adverse effects, suggesting this as the preferable application rate for balanced zinc nutrition. No significant varietal differences were observed in zinc accumulation ($P > 0.05$), indicating consistent zinc uptake patterns across all tested sorghum genotypes. The non-significant zinc × variety interaction ($P > 0.05$) further confirmed that the response to zinc application was uniform regardless of genetic background.

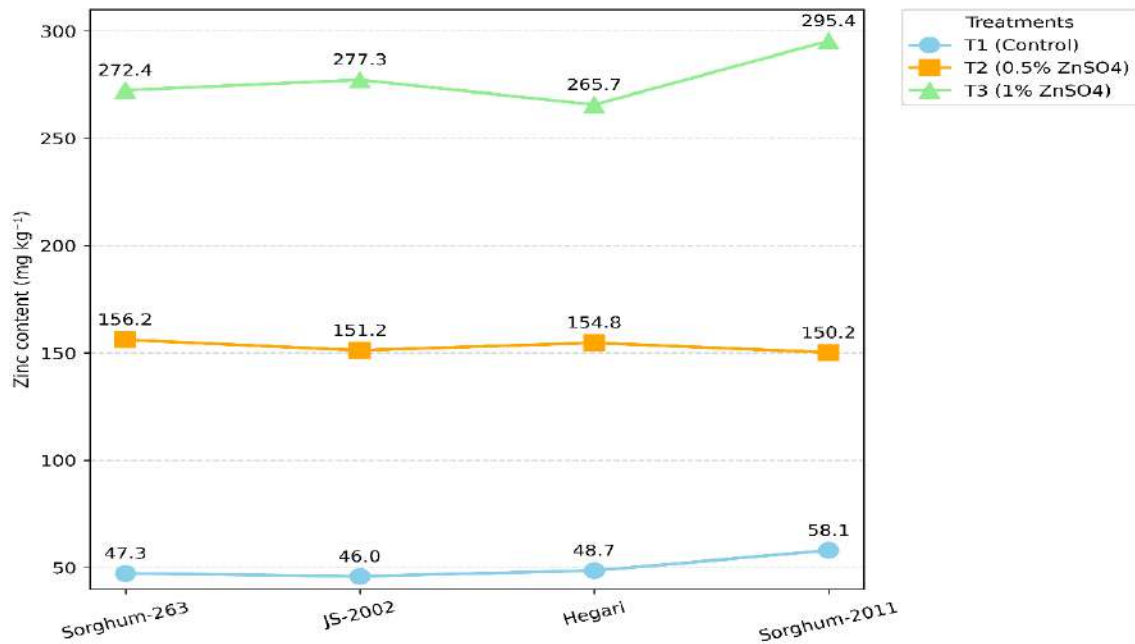


Figure 7. Effect of zinc concentration on Zinc content (mg kg⁻¹) of sorghum genotypes.

Correlation analysis

The correlation matrix reveals significant relationships among key sorghum parameters. Plant height shows strong positive correlations with leaf number (p<0.001) and yield (p<0.01), indicating their interdependence in growth performance. Notably, chlorophyll content demonstrates a significant positive association with both protein content (p<0.05) and zinc

concentration (p<0.01), suggesting enhanced photosynthetic activity contributes to improved nutritional quality. Fiber components (NDF and ADF) exhibit negative correlations with protein content (p<0.05), highlighting the trade-off between digestibility and nutritional value. These relationships emphasize the importance of balanced nutrient management for optimizing both yield and fodder quality in sorghum cultivation.

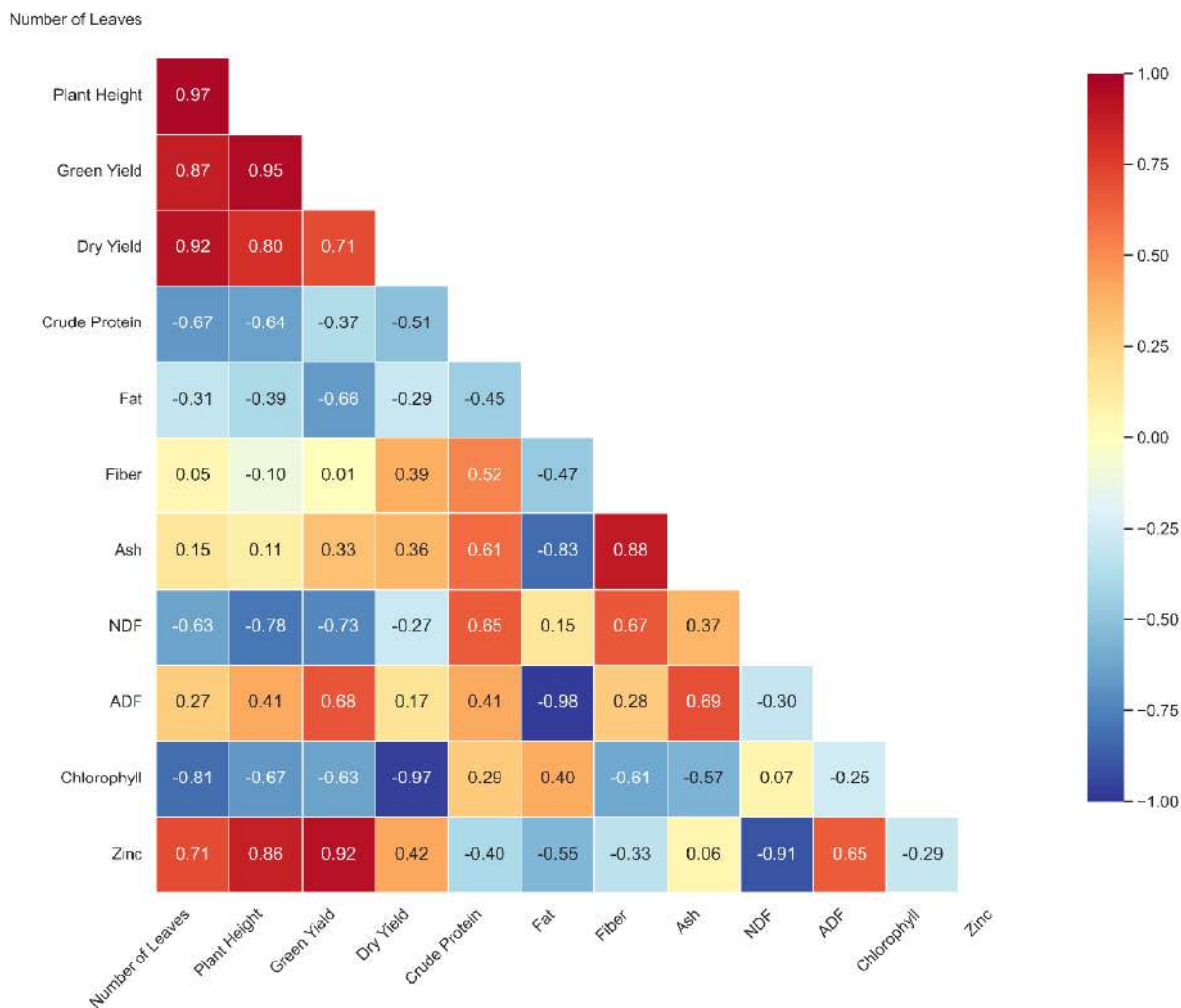


Figure 8. Correlation matrix of growth, yield, and nutritional quality parameters in sorghum (*Sorghum bicolor* L.) under different zinc treatments

Discussion

Climate change poses a significant threat to global food security by increasing the frequency of extreme weather events, including droughts, heatwaves, and erratic rainfall patterns (Schmidhuber & Tubiello, 2007). Forage crops, particularly fodder sorghum (*Sorghum bicolor* L.), play a crucial role in sustaining the livestock industry, especially in countries like Pakistan, by providing affordable and nutritious feed (Sarwar et al., 2002). However, optimal plant productivity depends on the availability of essential macro and micronutrients in appropriate quantities (Sajid et al., 2008). Among these, zinc (Zn) is a vital micronutrient that influences key physiological

and biochemical processes, including photosynthesis, protein synthesis, and nucleic acid metabolism (Cakmak, 2000; Jha, 2019). In Pakistan, zinc deficiency has become a major nutritional constraint after nitrogen (N) and phosphorus (P) deficiencies (Rashid & Rayan, 2004). This deficiency adversely affects critical plant functions such as germination, pollen viability, chlorophyll synthesis, and fertilization, ultimately reducing crop yield and quality (Kaya & Higgs, 2002). Furthermore, Zn-deficient sorghum can lead to health complications in livestock, as adequate Zn intake is essential for animal health and milk production (Asif et al., 2020). Research indicates that organically bound

Zn from green fodder enhances milk yield and reduces somatic cell counts in milk (Kinal et al., 2005). Cattle exhibit zinc deficiency symptoms when their feed contains less than 42 mg Zn per kg of dry matter, underscoring the importance of Zn-rich forage.

Zinc applications have been shown to improve both yield and nutritional quality in various crops. In wheat, soil application of ZnSO₄ (10 kg ha⁻¹) maximized grain yield (6.60 Mg ha⁻¹), while foliar application (0.5% ZnSO₄) significantly increased grain Zn content by 70% (Hassan et al., 2019). Similarly, in sorghum, combined soil and foliar Zn and iron (Fe) applications enhanced fodder yield and quality, including crude protein content (Pawar et al., 2015). Biofortification studies further demonstrated that foliar application of calcium (Ca, 3%), Zn (2%), and Fe (1%) increased sorghum dry matter yield by 120.8% and crude protein by 78.6% (Asif et al., 2020). In maize, soil Zn application (16 kg ha⁻¹) supplemented with foliar sprays (0.3% at 30 and 40 days after sowing) improved herbage yield by 25% and crude protein content (Kumar et al., 2024).

The method of Zn application significantly influences nutrient uptake and economic returns. Foliar sprays exhibit higher nutrient use efficiency due to lower input requirements (Hassan et al., 2019), whereas soil applications provide more consistent yield improvements (Sher et al., 2022). Economic analyses suggest that soil Zn application is more profitable for sorghum production, while foliar methods are superior for biofortification purposes (Hassan et al., 2019). Given the critical role of sorghum as a high-quality, fast-growing fodder crop, addressing Zn deficiency through biofortification is essential to enhance both forage productivity and livestock health. Effective Zn management strategies, including optimized soil and foliar applications, can significantly improve fodder quality, ensuring sustainable livestock production in the face of climate change challenges.

Conclusion

Foliar zinc (Zn) application represents an effective agronomic strategy for improving both the

productivity and nutritional quality of sorghum (*Sorghum bicolor* L.) fodder. Our findings reveal that the application of 0.5% ZnSO₄ solution produced optimal results, significantly enhancing several critical quality parameters. Specifically, this treatment increased crude protein content by 10.75% and elevated fat content to 3.91%, while simultaneously improving chlorophyll content - indicative of enhanced photosynthetic capacity. Significantly, the treatment reduced neutral detergent fiber (NDF) to 61.91% and acid detergent fiber (ADF) to 32.18%, suggesting improved digestibility of the fodder. The Zn concentration in plant tissues reached 153.13 mg kg⁻¹, representing effective biofortification without inducing toxicity symptoms. Conversely, the higher application rate of 1% ZnSO₄ manifested apparent phytotoxic effects, as demonstrated by reduced biomass production, decreased protein content (9.29%), and excessive Zn accumulation (272.37 mg kg⁻¹) in plant tissues. Notably, the response patterns were consistent across all four tested sorghum varieties (*Sorghum* 263, JS 2002, Hegari, and *Sorghum* 2011), indicating that the observed effects are likely genotype-independent and broadly applicable. Future research directions should focus on (1) evaluating the carry-over effects of Zn-biofortified fodder on livestock performance metrics, particularly milk yield and quality; (2) investigating the economic viability of this intervention at the farm scale; and (3) examining potential interactions between Zn application and other micronutrients in sorghum fodder production systems. Such studies would further validate and refine the practical application of these findings.

Author contributions

All authors have contributed to various aspects of the study, including conceptualization, writing, editing, and revisions.

Conflict of interest disclosure

The authors declare that they are entirely free from any financial or ties that may have influenced the results presented in this work.

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