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Agronomic bio-fortification of zinc on growth, yield and economics of grain sorghum [*Sorghum bicolor* (L.) Moench]

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Abstract
A field experiment was conducted during *kharif* 2024 at the Agricultural Research Station, Hagari, University of Agricultural Sciences, Raichur, to study the effect of agronomic biofortification of zinc in grain sorghum. The experiment was laid out in a randomized complete block design (RCBD) with three replications and ten treatments comprising different levels of soil and foliar applications of zinc sulfate ($ZnSO_4$).
The results revealed that the treatment receiving 20 kg $ZnSO_4$ ha^{-1} as a basal application along with foliar sprays of $ZnSO_4$ @ 0.5% each at 30 and 45 days after sowing (DAS) recorded significantly higher grain yield (3586 kg ha^{-1}), gross returns (₹1,48,480 ha^{-1}), net returns (₹99,953 ha^{-1}), and benefit-cost ratio (3.06). The study concluded that the combined application of 20 kg $ZnSO_4$ ha^{-1} as basal + foliar sprays of $ZnSO_4$ @ 0.5% at 30 and 45 DAS is the most effective treatment for enhancing grain yield and economic returns in sorghum through agronomic biofortification.

Keywords: Agronomic biofortification, zinc, foliar application, grain sorghum, yield enhancement

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench], commonly known as great millet, Indian millet, or milo, is an important cereal grain belonging to the grass family (*Poaceae*). It plays a vital role in ensuring food and nutritional security, particularly in arid and semi-arid regions. Increasing sorghum production and productivity has become crucial to meet the growing demand associated with the rising population.

In India, sorghum is cultivated over an area of 4.07 million hectares with a total production of 4.73 million tonnes and an average productivity of 1162 kg ha^{-1}. In Karnataka, the crop covers about 0.8 million hectares with a production of 0.94 million tonnes and productivity of 1167 kg ha^{-1} (Anon., 2025a) [1].

Globally, sorghum is utilized in multiple forms such as baked products, grilled preparations, and both alcoholic and non-alcoholic beverages. Nutritionally, grain sorghum is a rich source of starch and protein, and being naturally gluten-free, it serves as a valuable dietary component for individuals with celiac disease (Ratnavathi and Komala, 2016) [2]. The crude oil content in sorghum grains ranges from 3.58 to 3.91%, of which about 84% comprises oleic and linoleic acids. Moreover, the presence of phenolic compounds, flavonoids, and various antioxidants enhances its nutritional and health-promoting value. These bioactive components help in reducing oxidative stress and lowering the risk of several chronic diseases such as cancer and rheumatoid disorders (Rashawn *et al*., 2021) [3].

Despite its diverse uses and nutritional importance, the productivity of sorghum remains low, primarily because it is often cultivated on marginal lands with limited nutrient inputs and an imbalanced use of macronutrients. Among micronutrients, zinc (Zn) deficiency has emerged as one of the most widespread nutritional constraints in soils and crops worldwide, leading to significant yield losses and reduced grain quality (Sillanpää, 1982) [4].

Genetic biofortification through plant breeding is a promising long-term strategy for enhancing

Zn concentration in grains. However, it is a time-consuming process that demands sustained efforts and resources. As a short-term and more practical approach, agronomic biofortification—through the application of Zn fertilizers to soil and/or foliage—offers an effective means to increase Zn concentration in cereal grains while simultaneously improving yield and crop quality.

Materials and Methods

The field experiment was conducted during *kharif* 2024 at the Agricultural Research Station, Hagari, University of Agricultural Sciences, Raichur, Karnataka. The research station is situated in Agro-Climatic Zone III (Northern Dry Zone) of Karnataka at a latitude of 15°13′ N, longitude of 77°05′ E, and an altitude of 414 meters above mean sea level.

The experimental soil was medium black clay in texture, classified under the order *Vertisols*, with a pH of 7.65 and an electrical conductivity (EC) of 0.52 dS m^{-1}. The soil was low in available nitrogen (252.80 kg ha^{-1}), medium in available phosphorus (40.90 kg P_2O_5 ha^{-1}) and potassium (425.20 kg K_2O ha^{-1}), low in zinc (0.32 mg kg^{-1}), and low in organic carbon (5.30 g kg^{-1}).

The experiment was laid out in a Randomized Complete Block Design (RCBD) with ten treatments replicated three times. The treatments consisted of different levels of soil-applied and foliar-applied zinc sulfate ($ZnSO_4$) as follows:

- **T_1:** Soil application of 10 kg $ZnSO_4$ ha^{-1}
- **T_2:** 10 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS
- **T_3:** 10 kg $ZnSO_4$ ha^{-1} as basal + foliar sprays of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS
- **T_4:** Soil application of 15 kg $ZnSO_4$ ha^{-1} (recommended dose of zinc, RDZn)
- **T_5:** 15 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS
- **T_6:** 15 kg $ZnSO_4$ ha^{-1} as basal + foliar sprays of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS
- **T_7:** Soil application of 20 kg $ZnSO_4$ ha^{-1}
- **T_8:** 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS
- **T_9:** 20 kg $ZnSO_4$ ha^{-1} as basal + foliar sprays of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS
- **T_{10}:** Absolute control (no Zn application)

The recommended dose of fertilizers (RDF) applied to all treatments was 100:50:75:37.5 kg N:P_2O_5:K_2O:Zn ha^{-1}. Half of the nitrogen and the entire doses of phosphorus and potassium were applied as basal, while the remaining half of nitrogen was top-dressed at 30 days after sowing (DAS).

Plant height was recorded from five randomly selected and tagged plants in each treatment at 30-day intervals, measured from the ground level to the base of the fully expanded top leaf. Grain and straw yields were recorded at harvest, and the economics of different treatments were worked out based on the prevailing market prices during the experimental period.

The recorded data were statistically analyzed using the Analysis of Variance (ANOVA) technique as outlined by Panse and Sukhatme (1967) [5], and treatment means were compared at a 5% level of significance.

Results and Discussion

Growth Parameters

Plant height

Plant height of sorghum at harvest was influenced by the application of different levels of zinc sulphate applied through soil and foliar spray (Table 1). Treatment receiving 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS recorded significantly higher plant height (153.3 cm) found on par with 15 kg $ZnSO_4$ ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (152.3 cm), 20 kg Zn ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% 45 DAS (152.1 cm), 15 kg $ZnSO_4$ ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% 45 DAS (150.8 cm) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (150.1 cm). Significantly shorter plants were recorded in absolute control (128.5 cm). The enhancement in plant height due to $ZnSO_4$ application could be attributed to its role in promoting meristematic activity, auxin synthesis and elongation of internodes which together improve overall vegetative growth and plant stature. Similar results were reported by Zayed *et al*. (2011) in rice crop [6].

Total dry matter production

Total dry matter production and its accumulation at various growth stages was significantly affected by the application of different levels of zinc sulphate applied through soil and foliar spray (Table 1). Significantly higher total dry matter accumulation at harvest was noticed in 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (216.1 g $plant^{-1}$) found on par with 15 kg $ZnSO_4$ ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (213.9 g $plant^{-1}$), 20 kg Zn ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% 45 DAS (213.9 g $plant^{-1}$), 15 kg $ZnSO_4$ ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% 45 DAS (212.3 g $plant^{-1}$) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (210.7 g $plant^{-1}$). Whereas, absolute control recorded the least dry matter (145.3 g $plant^{-1}$) among the treatments. The increase in total dry matter accumulation with combined soil and foliar application of zinc is primarily due to enhanced vegetative growth, including greater plant height, expanded leaf area and improved stem and earhead biomass. Zinc facilitates chlorophyll formation, protein biosynthesis and energy transduction, thereby boosting photosynthetic efficiency and dry matter production. Additionally, better nutrient uptake and transport, particularly under zinc-enriched conditions, improves source activity and assimilate partitioning towards various plant organs. Similar results were reported by Kubsad (2019) [7] and Batubara *et al*. (2023) [8].

Yield parameters and yield

Earhead weight

Application of 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS recorded significantly higher ear head weight (89.7 g) as compared to other treatments and was found on par with 15 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (88.4 g), 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (86.4 g), 15 kg $ZnSO_4$ ha^{-1}+ foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (84.2 g) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (84.3 g). In contrast, significantly least ear head weight was observed in absolute control (60.1 g). The notable improvement in ear head weight under combined basal and foliar zinc application could be attributed to enhanced zinc availability during critical reproductive stages, which supports panicle development by promoting pollen viability and spikelet fertility. Zinc-mediated activation of enzymatic systems such as carbonic anhydrase and dehydrogenases may have supported increased photosynthate production and efficient nutrient partitioning towards the developing panicle. Similar kind of outcomes were noticed by Kubsad (2019) [7] in sorghum crop.

Grain weight

Among different treatments, application of 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS recorded significantly higher grain weight (58.1 g plant^{-1}) as compared to other treatments and was found on par with 15 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (57.8 g plant^{-1}), 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (57.2 g plant^{-1}), 15 kg $ZnSO_4$ ha^{-1}+ foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (56.7 g plant^{-1}) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (56.3 g plant^{-1}). In contrast, significantly least grain weight was recorded in absolute control (34.9 g plant^{-1}). Higher grain weight under combined zinc application is attributed to better grain filling due to improved photosynthetic rate, efficient assimilate translocation and enhanced enzyme activity involved in starch and protein synthesis. Zinc also stabilizes membrane integrity and supports hormonal balance during grain development. These results were similar with findings of Kubsad (2019) [7] in sorghum crop and Sharanappa *et al*. (2019) in pearl millet crop.

Grain yield

Significantly higher grain yield was recorded in treatment receiving 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (3586 kg ha^{-1}) as compared to other treatments and was found on par with 15 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (3484 kg ha^{-1}), 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (3405 kg ha^{-1}), 15 kg $ZnSO_4$ ha^{-1}+ foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (3353 kg ha^{-1}) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (3267 kg ha^{-1}). In contrast, significantly lower grain yield was observed in absolute control (2025 kg ha^{-1}).

Significantly enhanced the grain yield of sorghum, which can be attributed to improved plant growth parameters such as increased leaf area, higher dry matter accumulation and superior yield attributes like number of grains per panicle and test weight. Zinc plays a crucial role in auxin synthesis, chlorophyll formation, and enzymatic activation, which collectively promote cell division and expansion, leading to robust vegetative growth and efficient translocation of photosynthates to reproductive parts. This ultimately resulted in better grain filling and higher productivity. Furthermore, improved plant vigor and source-sink dynamics under zinc-enriched treatments support higher productivity. Similar results were reported by Jan *et al.* (2013) [9] and Kubsad (2019) [7].

Stover yield

Application of 20 kg $ZnSO_4$ ha^{-1} as basal along with foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS resulted in higher stover yield (9202 kg ha^{-1}), which was statistically comparable to 15 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (9259 kg ha^{-1}), 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (8861 kg ha^{-1}), 15 kg Zn ha^{-1} + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (8634 kg ha^{-1}) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (8623 kg ha^{-1}). However, significantly lower stover yield (5824 kg ha^{-1}) was recorded under the absolute control.

The enhanced stover yield under zinc application can be attributed to increased cell division, expansion, and enhanced photosynthetic efficiency, which collectively contribute to better biomass production. Zinc plays a pivotal role in protein synthesis and metabolic activities that promote vegetative growth, resulting in higher accumulation of structural biomass. Additionally, improved nutrient uptake and chlorophyll stability enhance overall plant vigor, ultimately contributing to greater stover output. Similar results were reported by Choudhary *et al.* (2015) [10] and Sharanappa *et al*. (2019) [11].

Table 1: Growth parameters, yield parameters and yield of sorghum as influenced by agronomic bio-fortification of zinc at different level

Treatment	Plant height (cm)	Total dry matter production (g plant^{-1})	Earhead weight (g)	Grain weight (g plant^{-1})	Grain yield (kg ha^{-1})	Stover yield (kg ha^{-1})
T_1	136.2	180.7	67.1	41.2	2925	7945
T_2	141.2	188.7	69.3	46.2	3029	7992
T_3	144.0	195.9	73.6	51.3	3051	8036
T_4	143.4	195.5	71.1	50.2	3075	8066
T_5	150.8	212.3	84.2	56.7	3353	8634
T_6	152.3	213.9	88.4	57.8	3484	9259
T_7	150.1	210.7	84.3	56.3	3267	8623
T_8	152.1	213.9	86.4	57.2	3405	8861
T_9	153.3	216.1	89.7	58.1	3586	9202
T_{10}	128.5	145.3	60.1	34.9	2025	5824
S.Em.±	3.0	5.2	1.9	2.1	117	315
C.D. (P=0.05)	8.9	15.5	5.7	6.2	348	935

Note:

- RDF-100:75:37.5:15 kg $N:P_2O_5:K_2O:ZnSO_4$ ha^{-1}; FYM @ 5.5 t ha^{-1} is common for all the treatments except absolute control
- Half of N, entire P_2O_5, K_2O and $ZnSO_4$ was applied as basal and remaining half of N was side dressed at 30 days after sowing

Economics

Application of 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS recorded significantly higher cost of cultivation (Rs.48,527 ha^{-1}), followed by soil application of 15 kg $ZnSO_4$ ha^{-1} as basal + Foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (Rs.48,104 ha^{-1}). However, lower cost of cultivation was observed with absolute control (Rs.33,246 ha^{-1}) (Table 2).

Significantly higher gross returns, net returns and B C ratio were recorded in treatment received application of 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (Rs. 148480 ha^{-1}, Rs. 99953 ha^{-1} and 3.06) as compared to other treatments and was found on par with 15 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS (Rs. 145231 ha^{-1}, Rs. 97127 ha^{-1} and 3.02), 20 kg $ZnSO_4$ ha^{-1} as basal + foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (Rs. 141356 ha^{-1}, Rs. 93768 ha^{-1} and 2.97), 15 kg $ZnSO_4$ ha^{-1}+ foliar spray of $ZnSO_4$ @ 0.5% at 45 DAS (Rs.138915 ha^{-1}, Rs. 91670 ha^{-1} and 2.94) and 20 kg $ZnSO_4$ ha^{-1} as basal alone (Rs.136015 ha^{-1}, Rs. 89295 ha^{-1} and 2.91). Whereas, gross returns, net returns and B C ratio were significantly lower with absolute control (Rs.85726 ha^{-1}, Rs. 52480 ha^{-1} and 2.58).

The increased higher gross returns, net returns and B C ratio under the combined basal and foliar zinc application treatment may be attributed to enhanced yield performance resulting from improved nutrient use efficiency and better crop vigor. Similar results were reported by Vinita *et al*. (2021) [12] and Singh *et al*. (2022) [13].

Table 2: Economics of sorghum as influenced by the application of different levels of zinc as soil applied and foliar spray

Treatment	Cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	BC ratio
T_1	45650	122422	76772	2.68
T_2	46465	126076	79611	2.71
T_3	47147	126948	79801	2.69
T_4	46152	127871	81719	2.77
T_5	47245	138915	91670	2.94
T_6	48104	145231	97127	3.02
T_7	46720	136015	89295	2.91
T_8	47588	141356	93768	2.97
T_9	48527	148480	99953	3.06
T_{10}	33246	85726	52480	2.58
S.Em.±	-	4151	4151	0.09
C.D. (P=0.05)	-	12335	12335	0.27

Note:

- RDF-100:75:37.5:15 kg N:P_2O_5:K_2O:$ZnSO_4$ ha^{-1}; FYM @ 5.5 t ha^{-1} is common for all the treatments except absolute control
- Half of N, entire P_2O_5, K_2O and $ZnSO_4$ was applied as basal and remaining half of N was side dressed at 30 days after sowing

Conclusion

The present field investigation clearly demonstrated that zinc plays a pivotal role in improving the growth, yield, and economic returns of grain sorghum. Among the different levels and methods of zinc sulphate application, the treatment comprising soil application of 20 kg $ZnSO_4$ ha^{-1} as basal along with foliar sprays of $ZnSO_4$ @ 0.5% each at 30 and 45 DAS proved to be the most effective. This treatment significantly enhanced growth parameters such as plant height and dry matter accumulation, which consequently resulted in higher grain yield, straw yield, gross returns, net returns, and a superior benefit-cost ratio compared to all other treatments.

The improvement in productivity can be attributed to better zinc availability throughout the crop growth period, leading to enhanced photosynthetic activity, enzyme function, and efficient nutrient utilization. Hence, the combined application of zinc both to the soil and as foliar sprays ensures adequate and continuous supply of the nutrient, thereby optimizing crop performance under the conditions of the Northern Dry Zone of Karnataka [12-26].

From this study, it can be concluded that soil application of 20 kg $ZnSO_4$ ha^{-1} as basal + foliar sprays of $ZnSO_4$ @ 0.5% at 30 and 45 DAS is the most suitable and economically viable practice for achieving higher productivity and profitability in grain sorghum cultivation through agronomic biofortification.

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