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RESEARCH ARTICLE

Biofortification of zinc in sorghum grown in rainfed black soil (Typic Chromusterts)

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Abstract

Zinc (Zn) is a crucial micronutrient for crop growth and enzymatic regulations. The present study was formulated to reveal the effect of organic fortified Zn composite on the development and yield of sorghum. The field screening experiment was laid out in a factorial arrangement of Randomized Block Design (FRBD) with three replications. The treatments consisted of factor 1 were four microbial inoculants viz. M_1: Plant Growth-Promoting Rhizobacteria (PGPR), M_2: Zinc-Solubilizing Bacteria (ZSB), M_3: Vesicular-Arbuscular Mycorrhiza (VAM), M_4: Control, 100 % recommended NPK at 40:20:0 kg ha^{-1} with Zn was applied as a common dose to all treatment plots and 20 sorghum genotypes considered as another factor 2. Among the genotypes, the variety K12 recorded the highest Dry Matter Production (DMP) (5069 kg ha^{-1}) at vegetative and other genotypes like TKSV 1036, PYT CO 30, TKSV 1315 and TKSV 1307 recorded DMP of 4950, 4946, 4921 and 4910 kg ha^{-1} were found efficient and responsive. Among the screened genotypes K12 and TKSV 1036 were found to be responsive genotypes. Further, various zinc levels of field experiments II were conducted with the efficient and responsive genotypes K12 and TKSV 1036, which were studied by imposing fifteen treatments in a split plot design and replicated thrice. Higher mean Zn uptake of 10.4, 59.9 and 41.9 g ha^{-1} was also recorded by Zinc Solubilising Bacteria (M_1) at vegetative, flowering and harvest respectively. The highest grain yield of 4334 kg ha^{-1} was registered by S_{15}, which was comparable with S_{14} (4291 kg ha^{-1}). The highest grain zinc uptake of 48.42 g ha^{-1} was recorded with the application of S_9 + Zn-EOM at 50 kg ha^{-1}. Farmers in saline soil can adopt this integrated zinc nutrient management to enrich zinc and enhance the growth and yield of sorghum in potentially zinc-deficient soil.

Keywords: biofortification; microbial inoculants; sorghum; vermicompost; yield; zinc

Introduction

Micronutrient malnutrition because of zinc deficiency is a serious public health problem worldwide. Zinc deficiency in children causes stunting, makes them vulnerable to diarrhoea and pneumonia and can lead to death. Crop biofortification is increasingly being recognized as a cost-effective and sustainable approach to overcoming these deficiencies in the food chain. Globally, more than 30 % of soils are low in plant-available Zn. Compared with legumes, cereals are generally more prone to Zn deficiency leading to a substantial reduction in grain yield and nutritional quality especially the crops grown on soils low in available Zn generally produce low yields with poor nutritional quality. For instance, a significant decrease (80 %) in grain Zn concentration was observed in cereals are grown on soils with low plant-available Zn. This decrease in grain Zn also reduces its bioavailability in humans contributing to Zn deficiency in susceptible human populations. Worldwide micronutrient deficiency is an alarming threat to food insecurity and malnutrition. Therefore, biofortification through fertilization strategies in a crop like sorghum, also referred to as poor man's cereal is more beneficial in the aspect of enriching zinc in soil-plant-human continuum. In light of this, the present investigation was undertaken to enrich grain zinc density (biofortification) of sorghum crop, as an outlet to alleviate zinc deficiency in zinc-deficient soils (saline soils).

Materials and Methods

The field experiment I and II was conducted in farmer's field at Karisalkulam, Thoothukudi District, Tamil Nadu. The farm is situated at 9^{0}11'55.7" N latitude and 77^{0}88'91.3" E longitude with an elevation of 116 m above MSL in the state of Tamil Nadu. The identified farmer's field soil was clay loam in texture and taxonomically as called Typic Chromusterts. The soil is highly saline and deficient in zinc.

Representative surface soil samples (0-15 cm) were collected randomly from experimental sites before the experiment commenced using stainless steel material and a composite sample was prepared. The soil samples were processed and stored in polythene containers to study their various physical and chemical properties. The details on the initial physicochemical properties of the experimental soils are given in Table 1. The field experiment during the Rabi season was carried out with 20 sorghum genotypes. 10 tolerant, 5 moderate tolerant and 5 susceptible were selected from hydroponics. The characteristic

Table 1. Initial physico-chemical properties of the experimental soils

Sl. No.	Properties	Value
	A. Physical properties	
1.	Coarse sand (%)	25.8
2.	Fine sand (%)	17.9
3.	Silt (%)	22.5
4.	Clay (%)	33.8
5.	Texture	Clay loam
6.	Bulk density (mg m^{-3})	1.38
7.	Particle density (mg m^{-3})	2.41
8.	Porosity (%)	41.1
	B. Physico- chemical properties	
1.	pH	8.15
2.	EC (dS m^{-1})	0.39
3.	CEC (c mol (p^{+}) kg^{-1})	30.29
	C. Chemical properties	
1.	Organic carbon (g kg^{-1})	3.5
2.	Free CaCO3 (%)	12.5
3.	KMnO4 -N (kg ha^{-1})	242
4.	Olsen -P (kg ha^{-1})	12
5.	NH4OAc -K (kg ha^{-1})	416
6.	Exchangeable calcium (mg kg^{-1})	286
7.	Exchangeable magnesium (mg kg^{-1})	115
8.	Available sulphur (mg kg^{-1})	18.5
9.	DTPA- Zn (mg kg^{-1})	0.75
10.	DTPA- Fe (mg kg^{-1})	2.01
11.	DTPA- Cu (mg kg^{-1})	1.09
12.	DTPA- Mn (mg kg^{-1})	1.71
	D. Zinc fractions (mg kg^{-1})	
1.	Water soluble + Exchangeable Zn	0.574
2.	Organically bound Zn	1.062
3.	Manganese oxide bound Zn	0.339
4.	Amorphous sesquioxide Zn	2.360
5.	Crystalline sesquioxide	2.260
6.	Residual Zn	452.4
7.	Total Zn	459.0

features of the genotypes used are depicted in Table 2. The field chosen for screening the performance of sorghum genotypes was initially ploughed twice and then leveled thoroughly. The land configuration of ridges and furrows was formed. The individual plots were laid out with an area of 20 m^2. The treatment details are as follows, the main plots are different varieties of sorghum i.e. M_1: K 12 variety and M_2 as TKSV 1036 (Sorghum genotype, ARS, Kovilpatti) and 15 subplots i.e. S_1: Absolute control, S_2: RDF (without Zn), S_3: $ZnSO_4$ at 12.5 kg ha^{-1}, S_4: $ZnSO_4$ at 25 kg ha^{-1}, S_5: $ZnSO_4$ at 50 kg ha^{-1}, S_6: Zn-EOM at 12.5 kg ha^{-1}, S_7: Zn-EOM at 25 kg ha^{-1}, S_8: Zn-EOM at 50 kg ha^{-1}, S_9: Seed priming + Foliar spray + Zinc Solubilizing Bacteria (ZSB), S_{10}: S_9 + $ZnSO_4$ at 12.5 kg ha^{-1}, S_{11}: S_9 + $ZnSO_4$ at 25 kg ha^{-1}, S_{12}: S_9 + $ZnSO_4$ at 50 kg ha^{-1}, S_{13}: S_9 + Zn-EOM at 12.5 kg ha^{-1}, S_{14}: S_9 + Zn-EOM at 25 kg ha^{-1} and S_{15}: S_9 + Zn-EOM at 50 kg ha^{-1}. The experiment was laid out in a split plot design and replicated thrice. The field experiment was conducted with zinc-efficient sorghum genotypes of K12, TKSV 1036 chosen from best-performed experiment in soils having low zinc status and high salt content. The recommended dose of fertilizer (RDF) at 40:20:0 kg N, P_2O_5, K_2O ha^{-1} for TNAU dual sorghum was applied as a common dose to all treatment plots. The full dose of N and P was applied as basal. Zinc was also applied as basal dressing in the form of $ZnSO_4.7H_2O$ as per treatments.

The DMP was assessed treatment-wise at vegetative, flowering and harvest stages respectively. Grain samples that are well-filled were drawn from individual plots. The yield was calculated after calibrating the marked area yield to one hectare and expressed as kg ha^{-1}.

Results and Discussion

Dry matter production of different genotypes

The data furnished in Table 3 showed an increasing trend in dry matter yield of sorghum genotypes with the advancement of crop growth stages. Also, the dry matter production increased with a concomitant increase in levels of zinc. With soil application of zinc, the dry weight of the plant varied from 1190 to 1646, 3929 to 5445 and 7368 to 8792 kg ha^{-1} at vegetative, flowering and harvest stages respectively.

Table 2. Details on the genotypes chosen from the hydroponics experiment utilized in the study

Best responsive (10)	Moderate tolerant (5)	Susceptible (5)
TKSV 1012	K 8	SPV 2121
TKSV 1036	PYT CO30	TKSV 1003
TKSV 1143	AYT 1314	TKSV 1017
Kalanpatti chencholam	SPV 2104	TKSV 1307
Dharmapuri chencholam	Duraisamipuram chencholam	TNS 598
SPV 2118		
TKSV 1041		
K 12		
K 11		
TKSV 1315		

Table 3. Effect of zinc fertilization and microbial inoculants on dry matter production (kg ha^{-1}) of sorghum genotypes in various stages

Treatments		Vegetative (kg ha^{-1})					Flowering (kg ha^{-1})					Harvest (kg ha^{-1})				
		M_1 (RB)	M_2 (ZSB)	M_3 (VAM)	M_4 (Control)	Mean	M_1 (RB)	M_2 (ZSB)	M_3 (VAM)	M_4 (Control)	Mean	M_1 (RB)	M_2 (ZSB)	M_3 (VAM)	M_4 (Control)	Mean
G_1	TKSV 1012	1291	1407	1430	1219	1337	5028	5123	4370	3929	4613	7645	8473	8619	7368	8027
G_2	TKSV 1036	1425	1393	1638	1410	1467	4373	5445	5237	4743	4950	8546	8536	8648	8277	8502
G_3	TKSV 1041	1517	1641	1304	1353	1454	4254	4607	5117	4568	4637	8451	8531	7544	8272	8200
G_4	TKSV 1315	1378	1408	1330	1229	1337	4546	5325	5111	4701	4921	8541	7657	8255	8136	8148
G_5	TKSV 1143	1345	1330	1195	1418	1322	4340	5246	4865	4360	4703	8384	8600	7878	7975	8210
G_6	KCC	1296	1412	1568	1224	1375	4622	5128	4375	3934	4515	7650	8478	8708	7373	8053
G_7	DCC	1373	1200	1325	1224	1281	5227	4383	4375	4220	4552	7650	7662	8493	8141	7987
G_8	SPV 2118	1368	1195	1490	1601	1414	5148	4612	4516	4573	4713	8567	8782	7883	7980	8303
G_9	K12	1522	1646	1485	1606	1565	4632	5384	5237	5023	5069	8503	8750	8718	8614	8647
G_{10}	K11	1350	1611	1200	1415	1394	4345	4580	5116	4365	4602	8217	8792	8595	8332	8484
G_{11}	K8	1301	1340	1573	1423	1410	4627	5379	4870	3939	4704	8389	8745	8713	7378	8307
G_{12}	PYT CO30	1294	1470	1490	1611	1467	5320	4532	5389	4541	4946	8562	8421	8563	8207	8439
G_{13}	AYT 1314	1430	1221	1368	1358	1345	5153	5184	4521	4244	4776	8551	8620	8653	7534	8340
G_{14}	SPV 2104	1628	1226	1373	1527	1439	4919	4527	4578	4536	4640	8282	7796	8607	8553	8310
G_{15}	DPCC	1318	1616	1205	1328	1367	4350	4585	5100	5090	4782	8337	8787	7888	8327	8335
G_{16}	SPV 2121	1425	1345	1578	1335	1421	4914	4522	5122	4706	4816	8456	7791	8602	8212	8266
G_{17}	TKSV 1003	1485	1413	1190	1335	1356	4748	4378	4511	4215	4463	8503	8753	7652	8250	8290
G_{18}	TKSV 1017	1299	1475	1636	1398	1452	4602	5189	5330	4249	4843	8426	8625	8526	7539	8279
G_{19}	TKSV 1307	1633	1231	1388	1350	1401	5232	5440	4380	4225	4820	8755	7801	8416	8558	8383
G_{20}	TNS 598	1323	1621	1325	1435	1426	5241	4590	4711	5095	4910	7655	8748	8498	8146	8262
Mean		1400	1410	1405	1390	-	4781	4908	4842	4463	-	8304	8418	8373	8059	-
		G	M	GXM			G	M	GXM			G	M	GXM		
S.Ed		29	29	64			31	31	70			60	60	95		
CD (0.05 %)		59	59	133			65	65	145			125	125	279		

At the vegetative stage, among the different genotypes, K12 (G_9) recorded significantly higher dry matter production (1565 kg ha^{-1}) and was comparable with genotype TKSV 1036 (G_2). The significantly lowest dry matter production of 1281 kg ha^{-1} was registered by the genotype Duraisamipuram chencholam (DCC) (G_7). During the flowering stage, a significant maximum dry matter yield of 5069 kg ha^{-1} was observed for the genotype K 12 (G_9) and was followed by the genotype TKSV 1036 (G_2) with a dry matter yield of 4950 kg ha^{-1}, whereas significantly lower dry matter production of 4463 kg ha^{-1} was recorded by the genotype TKSV 1003 (G_{17}). At the harvest stage, a maximum dry matter production of 8647 kg ha^{-1} was recorded by the genotype K 12 (G_9), which was statistically comparable with TKSV 1036 (G_2) (8502 kg ha^{-1}). The lowest dry matter production of 7987 kg ha^{-1} was recorded by DCC (G_7).

As regards the performance of microbial inoculants, at vegetative, flowering and harvest stages, M_2 (ZSB) recorded significantly higher total dry matter production of 1410, 4908 and 8418 kg ha^{-1} respectively. The lower mean dry matter production was recorded by M_4 (control) with a value of 1390 kg ha^{-1} at vegetative stage, 4463 kg ha^{-1} at the flowering stage and 8059 kg ha^{-1} at the harvest stages respectively. The interaction effect between genotypes and microbial inoculants on dry matter content found to be significant at all stages of the crop. In the vegetative stage, the maximum dry matter content was recorded in G_9M_2 with a value of 1646 kg ha^{-1}. Significantly the lowest dry matter registered by $G_{17}M_3$ (1190 kg ha^{-1}).

Similarly maximum dry matter content of 5445 kg ha^{-1} was registered for G_2M_2, which was on par with $G_{12}M_3$ (5389 kg ha^{-1}) and $G_{11}M_2$ (5379 kg ha^{-1}) at the flowering stage. The lowest dry matter production was found to be recorded by G_1M_4 (3929 kg ha^{-1}), which was followed by G_6M_4 (3934 kg ha^{-1}) and $G_{11}M_4$ (3939 kg ha^{-1}) statistically on par with each other. At the harvest stage, the higher dry matter production was registered by $G_{10}M_2$ (8792 kg ha^{-1}) and it was on par with $G_{15}M_2$ (8787 kg ha^{-1}). The lowest dry matter production of 7368 kg ha^{-1} was recorded by G_1M_4 at harvest stage.

Grain zinc uptake of different genotypes

Soil application of zinc showed a marked variation concerning zinc uptake of sorghum genotypes (Table 4). The mean values of zinc uptake ranged from 6.3 to 15.5 g ha^{-1} at vegetative, 10.3 to 97.9 g ha^{-1} at flowering and 16.5 to 67.1 g ha^{-1} in the harvest stage. Soil application of zinc to sorghum genotypes, microbial inoculants and their interactions with zinc uptake were found to be non-significant in the vegetative stage. In the flowering stage, a higher zinc uptake of 62.1 g ha^{-1} was recorded by K 12 (G9) followed by the genotype TKSV 1036 (G2) (55.7 g ha^{-1}) which differed significantly from each other. The significantly lowest zinc uptake of 10.3 g ha^{-1} was recorded by TKSV 1041 (G3). Higher zinc uptake of 67.1 g ha^{-1} was recorded by K 12 (G_9) followed by PYT CO 30 (G_{12}) were statistically on par with each other. The lowest zinc uptake of 16.5 g ha^{-1} was recorded by TNS 589 (G_{20}) at the harvest stage.

Table 4. Effect of zinc fertilization and microbial inoculants on zinc uptake (g ha^{-1}) of sorghum genotypes in various stages

Treatments		Vegetative (g ha^{-1})					Flowering (g ha^{-1})					Harvest (g ha^{-1})				
		M_1 (RB)	M_2 (ZSB)	M_3 (VAM)	M_4 (Control)	Mean	M_1 (RB)	M_2 (ZSB)	M_3 (VAM)	M_4 (Control)	Mean	M_1 (RB)	M_2 (ZSB)	M_3 (VAM)	M_4 (Control)	Mean
G_1	TKSV 1012	10.3	10.5	6.8	9.1	9.2	25.6	50.7	19.6	39.4	33.8	17.1	48.5	23.9	24.7	28.5
G_2	TKSV 1036	9.8	12.6	14.5	8.2	11.3	58.6	47.4	49.2	67.6	55.7	42.2	34.3	45.0	33.3	38.7
G_3	TKSV 1041	7.6	14.4	10.9	6.8	9.9	10.3	86.9	39.8	37.3	43.6	32.9	45.1	21.5	35.3	33.7
G_4	TKSV 1315	7.8	7.1	15.0	7.5	9.3	14.7	49.9	58.3	19.6	35.6	24.6	33.8	42.6	25.3	31.6
G_5	TKSV 1143	8.8	6.9	8.7	11.2	8.9	34.8	22.6	43.8	52.0	38.3	32.0	27.0	25.0	42.8	31.7
G_6	KCC	9.2	10.4	13.2	9.0	10.5	25.3	51.4	67.9	40.1	46.2	16.8	49.2	43.9	25.4	33.8
G_7	DCC	11.1	9.7	6.4	9.0	9.1	46.7	42.6	32.3	40.1	40.4	29.9	28.3	34.5	25.4	29.5
G_8	SPV 2118	7.5	15.5	8.0	13.3	11.1	11.0	86.6	17.4	71.7	46.7	33.6	44.8	25.1	45.9	37.3
G_9	K12	11.2	8.6	13.1	13.4	11.6	40.1	72.5	86.2	49.6	62.1	38.6	67.1	25.4	39.0	42.5
G_{10}	K11	9.9	12.7	7.9	14.4	11.2	25.0	67.2	68.6	52.7	53.4	32.7	66.4	25.7	26.0	37.7
G_{11}	K8	10.3	6.5	13.1	11.1	10.3	46.0	42.9	50.5	71.0	52.6	21.8	49.8	44.4	33.5	37.4
G_{12}	PYT CO30	14.0	8.7	10.8	8.6	10.5	39.4	71.8	18.1	71.4	50.2	39.3	66.8	26.3	25.0	39.3
G_{13}	AYT 1314	12.2	7.8	6.3	10.1	9.1	27.3	97.9	44.2	27.7	49.3	21.1	49.1	25.8	45.6	35.4
G_{14}	SPV 2104	7.7	8.8	10.9	6.7	8.5	57.9	47.7	53.8	10.7	42.5	29.6	27.3	35.2	25.1	29.3
G_{15}	DPCC	6.6	14.0	9.7	7.6	9.5	15.4	47.0	53.1	38.0	38.4	29.2	28.6	40.9	45.2	36.0
G_{16}	SPV 2121	6.9	6.4	14.2	7.4	8.7	18.9	67.9	68.3	32.7	46.9	23.2	38.4	44.3	34.9	35.2
G_{17}	TKSV 1003	13.2	7.7	8.7	7.4	9.2	49.8	25.7	42.2	32.7	37.6	40.2	28.0	27.9	34.9	32.7
G_{18}	TKSV 1017	8.7	14.1	8.6	7.4	9.7	35.5	97.2	44.5	20.3	49.4	25.3	33.6	44.3	36.0	34.8
G_{19}	TKSV 1307	13.9	9.8	7.2	7.5	9.6	46.4	25.0	33.0	39.8	36.0	42.9	34.0	33.1	38.1	37.0
G_{20}	TNS 598	6.5	15.1	7.0	8.8	9.4	28.0	97.6	21.9	15.1	40.6	16.5	37.7	44.6	43.5	35.6
Mean		9.7	10.4	10.0	9.2	-	32.8	59.9	45.6	41.5	-	29.5	41.9	34.0	34.2	-
		G	**M**	**GXM**			**G**	**M**	**GXM**			**G**	**M**	**GXM**		
S.Ed		2.1	2.1	4.2			2.2	2.2	4.4			3.2	3.2	6.4		
CD (0.05 %)		NS	NS	NS			4.4	4.4	NS			6.4	6.4	12.8		

With regard to microbial inoculants, the application of zinc in soil markedly influenced the zinc uptake in all the growth stages of crop. The maximum zinc uptake of 59.9 kg ha^{-1} and 41.9 kg ha^{-1} by M_2 (ZSB) was observed in the flowering and harvest stages respectively. Similarly, M_1 (RB) recorded the lowest zinc uptake 32.8 and 29.5 g ha^{-1} in the flowering and harvest stages respectively.

The interaction between soil application of zinc with genotypes and microbial inoculants showed significant variations in zinc uptake at 5 % level in the harvest stage. Further close scrutiny of data revealed that the interaction between soil application with genotypes and microbial inoculants recorded a maximum zinc uptake of 67.1 g ha^{-1} by G_9M_2. The lowest zinc uptake was recorded by $G_{19}M_1$ (16.5 g ha^{-1}).

Grain and stover yield with harvest index

The application of zinc in the form of enriched manures was found to have influenced grain yield (Table 5). The maximum grain yield (2356 kg ha^{-1}) was recorded in the treatment M_1 (K 12) followed by the treatment M_2 (TKSV 1036) (2250 kg ha^{-1}) which were found to be significantly different from each other. Among the different zinc levels, the application of Zn-EOM at 50 kg ha^{-1} along with seed priming (0.5 % $ZnSO_4$) + Foliar Spray 0.5 % Zn EDTA at 15, 30 and 45 DAS + ZSB (2 kg ha^{-1}) recorded the highest yield of 3292 kg ha^{-1} (S_{15}), followed by S_{14} (2885 kg ha^{-1}), S_{13} (2836 kg ha^{-1}), S_{12} (2667 kg ha^{-1}) and S_{11} (2394 kg ha^{-1}) which were comparable from each other. The treatment (S_1) received the lowest grain yield of 1507 kg ha^{-1}. The genotypes with treatment interactions on grain yield were found non-significant.

Higher stover yield (3937 kg ha^{-1}) was recorded by treatment M_1 (K 12) which was significantly different from each other with M_2 (TMSV 1036) (3847 kg ha^{-1}). Among the different levels of zinc application on sorghum genotypes, the significantly highest stover yield of 4867 kg ha^{-1} was observed in S_{15} (S_9 + Zn-EOM at 50 kg ha^{-1}) and it was on par with S_{14} (S_9 + Zn-EOM at 25 kg ha^{-1}) and S_{13} (S_9 + Zn-EOM at 12.5 kg ha^{-1}) with the stover yield of 4576 kg ha^{-1} and 4405 kg ha^{-1} respectively. The interaction effect of zinc × sorghum genotypes on stover yield was non-significant at 5 % level.

Harvest Index did not vary among the treatments with the application of various NPK combinations. The harvest index varied from 33.6 % to 40.3 % among all the treatments.

Plant zinc uptake

All different soil application treatments on sorghum genotypes showed a significant influence on the Zn uptake (Table 6). The observed range was from 68.3 to 436.7 kg ha^{-1} during the vegetative stage, 296 to 1660 kg ha^{-1} during the flowering stage and 899.4 to 1605.3 kg ha^{-1} during the harvest stages respectively. In main plots, Zn uptake of sorghum genotypes was significantly influenced by soil application of zinc fertilizer. K 12 (M_1) (196.5, 947.2 and 1361.6 kg ha^{-1}) recorded the highest value which was significantly different from TKSV 1036 (M_2) (160.8, 820.7 and 1342.9 kg ha^{-1}) at vegetative, flowering and harvest stages respectively. Within the subplots with different zinc levels of zinc application, significantly higher Zn uptake was observed in S_{15} (S_9+ Zn-EOM at 50 kg ha^{-1}) (369.8 and 1540.8 kg ha^{-1}) at vegetative and flowering stages respectively. This was followed by S_{14} (S_9+ Zn-EOM at 25 kg

Table 5. Effect of zinc fertilization on grain yield (kg ha^{-1}), stover yield (kg ha^{-1}) and harvest index of sorghum genotypes

Treatments	Grain yield (kg ha^{-1})			Stover yield (kg ha^{-1})			Harvest index		
	M_1	M_2	Mean	M_1	M_2	Mean	M_1	M_2	Mean
S_1	1597	1417	**1507**	3250	2732	**2991**	32.9	34.2	**33.6**
S_2	1759	1720	**1740**	3198	3196	**3197**	35.5	35.0	**35.2**
S_3	1882	1834	**1858**	3142	3256	**3199**	37.5	36.0	**36.7**
S_4	1993	1870	**1932**	3567	3352	**3460**	35.8	35.8	**35.8**
S_5	2209	2029	**2119**	3783	3512	**3648**	36.9	36.6	**36.7**
S_6	2082	1916	**1999**	3535	3551	**3543**	37.1	35.0	**36.1**
S_7	2187	2130	**2159**	3836	3767	**3802**	36.3	36.1	**36.2**
S_8	2802	2731	**2767**	4247	4204	**4226**	39.8	39.4	**39.6**
S_9	2154	2168	**2161**	4081	4050	**4066**	34.5	34.9	**34.7**
S_{10}	2301	2159	**2230**	4163	4113	**4138**	35.6	34.4	**35.0**
S_{11}	2484	2303	**2394**	4168	4143	**4156**	37.3	35.7	**36.5**
S_{12}	2686	2647	**2667**	4184	4043	**4114**	39.1	39.6	**39.3**
S_{13}	2880	2792	**2836**	4420	4389	**4405**	39.5	38.9	**39.2**
S_{14}	2958	2811	**2885**	4558	4594	**4576**	39.4	38.0	**38.7**
S_{15}	3366	3217	**3292**	4924	4810	**4867**	40.6	40.1	**40.3**
Mean	**2356**	**2250**	-	**3937**	**3847**	-	**37.2**	**36.6**	-
	M	**S**	**MXS**	**M**	**S**	**MXS**	**M**	**S**	**MXS**
S.Ed	32	32	72	43	43	96	0.22	0.22	0.51
CD (0.05 %)	67	67	NS	90	90	NS	NS	NS	NS

Table 6. Effect of zinc fertilization on plant Zn uptake (g ha^{-1}) of sorghum genotypes at various stages

Treatments	Vegetative (g ha^{-1})			Flowering (g ha^{-1})			Harvest (g ha^{-1})		
	M_1	M_2	Mean	M_1	M_2	Mean	M_1	M_2	Mean
S_1	82.0	68.3	**75.1**	438.5	296.0	**367.3**	1306.8	1227.8	**1267.3**
S_2	93.9	91.3	**92.6**	499.0	484.0	**491.5**	1208.2	1209.9	**1209.1**
S_3	116.3	105.8	**111.1**	639.1	529.6	**584.3**	1241.5	1138.8	**1190.2**
S_4	124.7	110.6	**117.7**	672.1	587.3	**629.7**	1359.3	1416.4	**1387.9**
S_5	128.7	113.4	**121.1**	689.1	620.3	**654.7**	1333.6	1385.8	**1359.7**
S_6	153.5	138.5	**146.0**	805.2	734.5	**769.9**	1083.4	1329.5	**1206.5**
S_7	161.9	143.0	**152.4**	811.1	772.1	**791.6**	899.4	1362.5	**1131.0**
S_8	164.9	144.1	**154.5**	824.8	791.5	**808.1**	1402.5	1229.3	**1315.9**
S_9	179.4	175.2	**177.3**	836.8	833.8	**835.3**	1253.9	1341.1	**1297.5**
S_{10}	195.7	182.3	**189.0**	1029.7	901.0	**965.4**	1597.9	1130.1	**1364.0**
S_{11}	200.6	189.2	**194.9**	1069.5	902.6	**986.0**	1539.2	1157.9	**1348.6**
S_{12}	214.0	190.6	**202.3**	1134.0	1020.3	**1077.1**	1564.4	1699.5	**1631.9**
S_{13}	322.6	219.2	**270.9**	1486.3	1158.6	**1322.4**	1481.4	1358.5	**1419.9**
S_{14}	372.3	238.2	**305.3**	1612.8	1257.0	**1434.9**	1605.3	1568.6	**1586.9**
S_{15}	436.7	302.9	**369.8**	1660.0	1421.6	**1540.8**	1547.5	1587.7	**1567.6**
Mean	196.5	160.8		947.2	820.7		1361.6	1342.9	
	M	**S**	**MXS**	**M**	**S**	**MXS**	**M**	**S**	**MXS**
S.Ed	5.3	5.3	10.3	4	4	8.3	6	6	12
CD (0.05 %)	10.5	10.5	20.6	8	8	17	13	13	25

ha^{-1}) which had Zn uptake of 305.3 and 1434.9 kg ha^{-1}. During the harvest stage, the highest Zn uptake was recorded by S_{12} (1631.9 kg ha^{-1}) followed by S_{14} (1586.9 kg ha^{-1}). The lowest Zn uptake (75.1 and 367.3 kg ha^{-1} at vegetative and flowering was recorded in S_1 (absolute control) while S_7 (Zn-EOM at 25 kg ha^{-1}) recorded the lowest Zn uptake (1131.0 kg ha^{-1}) during harvest stage.

Main and subplot interaction was significant for all the treatments. The maximum Zn uptake was recorded by M_1S_{15} (436.7 and 1660.6 kg ha^{-1}) at the vegetative and flowering stages respectively and it was statistically different from M_2S_{15} (302.9 and 1421.6 kg ha^{-1}) while the treatment M_1S_{14} (1605.3 kg ha^{-1}) showed high Zn uptake and differed significantly from M_2S_{14} during harvest stage. Minimum Zn uptake of 68.3 and 296.0 kg ha^{-1} (vegetative and harvest stages respectively) was recorded by the interaction plot M_2S_1 while during the harvest stage, M_1S_7 showed the minimum value (899.4 kg ha^{-1}). Significant differences had been noticed among the interaction plots for all the treatments during all the crop growth stages.

Grain - zinc uptake

The treatments had a significant influence on the zinc uptake of sorghum genotypes, which ranged from 12.7 to 69.2 mg kg^{-1} (Table 7). In the main plot, the zinc uptake of sorghum genotypes owing to soil application of zinc was found to be significant. The maximum value was recorded by the genotype K 12 (M_1) (36.3 mg kg^{-1}), and it was on par with TKSV 1036 (M_2) (31.5 mg kg^{-1}) of the grain zinc. In subplots, among the different zinc levels, significantly higher zinc uptake was recorded by S_{15} (S_9+ Zn-EOM at 50 kg ha^{-1}) (69.2 mg kg^{-1}) in grain. This was followed by S_{14} (S_9+ Zn-EOM at 25 kg ha^{-1}) recorded zinc uptake of 58.3 mg kg^{-1}. The lowest zinc uptake (12.7 mg kg^{-1}) was recorded in S_1 (absolute control). A significant interaction was noticed between zinc applications with genotypes of the grain. The maximum zinc uptake was recorded by M_1S_{15} (74.7 mg kg^{-1}) of zinc uptake in grain and it was statistically comparable with M_2S_{15} (63.7 mg kg^{-1}) of zinc uptake in grain and the lowest zinc uptake of 11.1 mg kg^{-1} was recorded by M_2S_1 and

Table 7. Effect of zinc fertilization on grain zinc uptake (g ha^{-1}) of Sorghum genotypes

Treatments	Zinc (g ha^{-1})		
	M_1	M_2	Mean
S_1 - Absolute control	14.4	11.1	12.7
S_2 - RDF (without Zn)	16.4	15.5	15.9
S_3 - $ZnSO_4$ at 12.5 kg ha^{-1}	19.4	17.4	18.4
S_4 - $ZnSO_4$ at 25 kg ha^{-1}	21.1	18.0	19.5
S_5 - $ZnSO_4$ at 50 kg ha^{-1}	24.3	20.3	22.3
S_6 - Zn-EOM at 12.5 kg ha^{-1}	27.3	21.7	24.5
S_7 - Zn-EOM at 25 kg ha^{-1}	29.3	25.6	27.4
S_8 - Zn-EOM at 50 kg ha^{-1}	40.9	33.0	37.0
S_9 - Seed priming (0.5 % $ZnSO_4$) + Foliar spray 0.5 % Zn EDTA at 15, 30 and 45 DAS + ZSB (2 kg ha^{-1})	32.1	31.7	31.9
S_{10} - S_9 + $ZnSO_4$ at 12.5 kg ha^{-1}	36.8	33.0	34.9
S_{11} - S_9 + $ZnSO_4$ at 25 kg ha^{-1}	40.0	35.9	38.0
S_{12} - S_9 + $ZnSO_4$ at 50 kg ha^{-1}	45.7	42.1	43.9
S_{13} - S_9 + Zn-EOM at 12.5 kg ha^{-1}	58.8	49.7	54.2
S_{14} - S_9 + Zn-EOM at 25 kg ha^{-1}	62.7	54.0	58.3
S_{15} - S_9 + Zn-EOM at 50 kg ha^{-1}	74.7	63.7	69.2
Mean	36.3	31.5	
	M	**S**	**MXS**
S.Ed	0.8	0.8	0.2
CD (0.05 %)	1.8	1.8	0.4

was comparable with M_1S_1 (14.4 and mg kg^{-1}) of zinc uptake in grain.

The field experiment employed twenty genotypes and four microbial inoculants along with soil application of various zinc treatments to examine the influence of zinc and microbial inoculants versus the response of genotypes. The results inferred that application of different microbial inoculants along with zinc on vegetative and booting stages significantly increased the enzyme activity, content, uptake, yield and quality of all genotypes. However, the cultivars K 12, TKSV 1036, K11, TKSV 1012, Kalanpatti chencholam, Dharmapuri chencholam and SPV 2118 were found to be highly responsive to the externally applied iron and zinc fertilizers.

Total dry matter production

DMP was recorded at the three stages of sorghum genotypes and the impact of zinc application and microbial inoculants. Zinc sulphate application at 25 kg ha^{-1} along with microbial inoculants increased the DMP of sorghum genotypes K 12 (1565 kg ha^{-1}) compared to the control (1281 kg ha^{-1}). The increase in DMP in the presence of adequate zinc might be due to the induced auxin synthesis that promotes the growth of the plant (1, 2). This reduction in dry matter production without zinc application might be due to Zn shortage leading to slowdown of photosynthesis (3).

Zinc uptake

Considerable increase in Zn uptake was observed with the advancement in growth stages of the crop and with the application of zinc sulphate and microbial inoculants.

Highest Zn uptake of 67.1 g ha^{-1} was observed by the G_9M_2 and the lowest was recorded by $G_{19}M_1$. Higher DMP and Zn content might be the reason for higher zinc uptake under this treatment. Also, higher nutrient uptake in plants can be attributed to more availability of nutrients and more absorptive area due to microbial inoculation (4).

Among the inoculants, M_2 (VAM) registered maximum (10.4, 59.9 and 41.9 g ha^{-1}) of zinc uptake over control at all three stages of crop growth. It is expected that higher zinc content and DMP recorded due to the application of inoculants ZSB (M_2) have resulted in maximum zinc uptake under this treatment. Plants that received nutrients (100 % NPK + Zn at 25 kg ha^{-1}) in combination with microbial inoculants produced maximum growth which could be attributed to better availability of nutrients from the rhizosphere and due to congenial environment prevailed in the vicinity of the root zone for the persistence and perpetuation of beneficial microbial inoculants to perform the better task of nutrient mobilization. This might be due to the solubilization of insoluble soil Zn by the production of gluconic acid by the microbes (5). The overall increase in plant growth and nutrient uptake was the result of partly Zn solubilization and IAA production by the inoculants used. Similar results on nutrient uptake were recorded in rice (6) and common bean (7).

Field experiment II (Soil application zinc)

The field experiment employed two genotypes and fifteen different zinc levels and to examine the influence of zinc versus response of genotypes. According to the findings, applying vermicompost-enriched zinc boosted zinc availability, enzyme activity, content, absorption, yield and quality in all genotypes. The genotypes K 12, TKSV 1036 were shown to be particularly tolerant to externally supplied zinc fertilizers and salinity.

Total dry matter production

Sorghum genotypes' dry matter yield rose as a result of different treatments. There was a considerable rise in total dry matter output with crop growth progress in all genotypes. The dry matter production of sorghum is the manifestation of progress and expansion of many morphological characteristics, which is directly connected to yield. The dry matter production at various phases of crop development is indicative of the influence of treatments throughout crop growth. At all phases of crop development, the complete experimental field obtaining NPK with zinc fertilizers performed much better than the control.

The application of a 25 % additional dosage of zinc enriched form (Zn-EOM) led to a rise in plant growth regulators, which led to higher total dry matter production at all stages than the control.

Zinc's favourable effect on dry matter production may be attributed to tryptophan synthesis in plants. Tryptophan is a precursor for the manufacturing of growth regulators such as auxin, indole acetic acid and cytokine, which perform important roles in cell division, cell elongation and root growth, which would have augmented crop growth and nutrient uptake, resulting in a greater in vegetative growth and ultimately promoting the DMP (8-10).

K12 (M_1) was shown to be better in total dry matter production throughout all phases. The zinc ingested engages in plant metabolic processes and enhances the photosynthetic rate, which may result in higher in plant dry matter production. Increasing DMP has been linked to improved photosynthetic rates and also increased nutrient absorption and utilization (11). A constant rise in dry matter production witnessed with the imposed of enriched zinc may be attributed to the rise in root foraging capacity as a result of greater root development (10) which may have aided the plants to have enhanced uptake of lant nutrients and ultimately improved plant vegetative growth (12, 13).

Grain and stover yield

All the yield attributing characters viz. ear head length and 1000 grain weight were significantly reflected in the respective grain yield of the genotypes. Grain yield was found to be enhanced by the application of zinc in the form of enriched manures. Treatments with Zn-EOM at 50 kg ha^{-1} (M_1S_{15}) (3366 kg ha^{-1}) had the highest grain yield, followed by treatments with Zn-EOM at 25 kg ha^{-1} (M_2S_{15}) (3217 kg ha^{-1}). In M_1S_{15}, M_1S_{14} and M_2S_{13}, the percentage increase in yield over control was 16.1, 15.3 and 13.6 % respectively.

The treatments from M_1S_{15} to M_2S_{15} received zinc enhanced with vermicompost, which promoted continuous availability of these micronutrients throughout crop development, as shown by the higher growth parameters observed in this research. Application of zinc would have boosted biosynthesis, growth hormone, starch synthesis and maturity, which resulted in increasing seed weight (14) and grain yield (15).

The plots cultivated with K 12 (M_1) had the highest grain production of the two genotypes. As evidenced by the data recorded by those genotypes, application of recommended doses of fertilizers along with micronutrients like zinc in the chelated or vermicompost enriched form may have promoted plant growth characters and yield attributes like productive tillers, ear head length and grain weight, which would have improved the grain yield of the above-mentioned genotypes (16). Earlier study researchers noted similar grain yield findings with different genotypes (17-20). Increases in plant height, leaf area, number of tillers per plant and dry matter content of the plant were presumably responsible for the increase in stover yield. Vermicompost enhanced form treatments (Zn-EOM at 50 kg ha^{-1}) produced more stover. M_1 seemed to have the maximum stover yield among the various sorghum genotypes (K 12). With the provision of a balanced dose of NPK with zinc, increased stover yield is the result of a positive and synergistic interaction between nutrient supply and crop development, as evidenced by enhanced growth parameters (19, 21). Moreover, zinc is involved in the detoxification of reactive oxygen species (ROS), which plays a barrier role in the prevention of photo oxidative damage in chloroplasts, which would have promoted crop development (22). Similarly, iron supplementation would have increased the chlorophyll content, resulting in increased plant height by promoting vegetative growth, which in turn increased the crop's stover yield (23-25).

Zinc uptake

The uptake of zinc was higher with soil application of Zn-EOM at 50 kg ha^{-1} (M_1S_{15}) and Zn-EOM at 25 kg ha^{-1}(M_1S_{14}) compared to $ZnSO_4$ at 50 kg ha^{-1} (M_1S_{12}) and $ZnSO_4$ at 25 kg ha^{-1} (M_1S_{11}) at all growth stages of crop. The influence of chelated Zn over FYM enriched $ZnSO_4$ in crop growth and utilization was higher due to less retention and greater transport and movement of Zn chelate by plant roots. The uptake of zinc in grain (48.4 g ha^{-1}) and straw (1567 g ha^{-1}) was observed in treatment supplemented with Zn-EOM. This might be due to less fixation with soil application of chelated Zn (26) coupled with greater transport and movement of zinc chelate by plant roots over FYM enriched zinc. Further, enriched Zn applied increased the labile form of Zn during crop growth and enhanced the Zn content and uptake in maize (27).

The treatments, which received FYM-enriched zinc, recorded higher content and uptake of zinc next to Zn-EOM. It was documented increased zinc content by combined use of organics and mineral fertilizers (28). Application of farmyard manure enriched with zinc on decomposition produce a variety of biochemical substances, which would have stimulated the solubility of zinc that might have increased the availability of zinc and increased uptake of zinc by plants (29-32).

With regard to genotypes, the application of zinc in soil markedly influenced the zinc uptake in all the growth stages of crop. The maximum zinc uptake was recorded by K 12 (M_1) followed by TKSV 1036 (M_2). This may be attributed to differential ability of genotypes on absorption and transport of the nutrient during crop growth. Similar results were reported earlier in sorghum (33), maize (34), sorghum (25, 35).

Conclusion

The concept of biofortification of enriching nutrient density in economic part, targeting the soil-plant and human continuum facilitates enriching zinc from source to sink with sustainable supply chain scenario and thus recommending Zn fertilizers more judiciously as per levels of soil fertility could be the future key to maintain soil health and human nutrition. Integrated zinc nutrient management with the combination of the best Zn use efficient and responsive genotype of sorghum K 12 along with seed priming, ZSB and Zn-EOM plus foliar spray enhanced the growth, yield and zinc enrichment of sorghum in saline soil. The combination of 50 kg ha^{-1} $ZnSO_4$ as enriched vermicompost along with seed priming, foliar spray thrice plus ZSB with recommended dose of NPKgave higher grain yield (3292 kg ha^{-1}), zinc content of 2.22 mg kg^{-1} (in grain), over recommended NPK alone. Thus, zinc biofortification in sorghum (K 12) is recommended to overcome malnutrition and to improve livelihood and socioeconomic status of rainfed black soil farmers of Southern Tamil Nadu.

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Authors' contributions

RV carried out the experiment, analysed the data and BK wrote the manuscript. SM, MM and KM conceived, designed and coordinated the experiments and corrected the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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