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RESEARCH ARTICLE

Enhancement of zinc availability and yield performance of black gram (*Vigna mungo* L.) through zinc solubilizing bacteria in alkaline soils

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Abstract

The present study investigated the combined effects of zinc sulphate ($ZnSO_4$) and zinc solubilizing bacteria (ZSB) on black gram (*Vigna mungo* L.) growth and productivity in alkaline soils. Field experiments were conducted at two locations (Agricultural College and Research Institute, Madurai and Coastal Saline Research Centre, Ramanathapuram) during January 2022 using a randomized block design with eight treatments and three replications. The treatments included varying levels of $ZnSO_4$ (12.5, 18.75 and 25 kg ha^{-1}) with and without ZSB (500 mL ha^{-1}). Results showed that the combined application of $ZnSO_4$ (25 kg ha^{-1}) and ZSB (500 mL ha^{-1}) along with soil test-based NPK significantly enhanced plant growth parameters, including plant height (35.4 cm), shoot length (38.18 cm) and root nodules (27.4 per plant). This treatment also recorded the highest seed yield (851 kg ha^{-1}), DTPA-extractable zinc (1.72 mg kg^{-1}) and zinc uptake (84.73 g ha^{-1}). The second most effective treatment was $ZnSO_4$ at 18.75 kg ha^{-1} with ZSB, which demonstrated comparable results and superior zinc use efficiency. The study concluded that integrating ZSB with optimal $ZnSO_4$ doses offers an effective strategy for improving black gram productivity and zinc nutrition in alkaline soils.

Keywords : alkaline soil; black gram; yield attributes; zinc nutrition; zinc solubilizing bacteria; zinc sulphate

Introduction

Black gram (*Vigna mungo* L.) is a vital pulse crop, particularly in India, where it accounts for approximately 70 % of global production, yielding around 2.06 million tons annually from 3.11 million hectares (1, 2). It containing 25-26 % protein and 60 % carbohydrates, making it a significant dietary component for population (1, 3). Beyond its nutritional value, black gram enhances soil fertility through biological nitrogen fixation, which is crucial for sustainable agriculture (3, 4). Integrated nutrient management practices, including the application of organic fertilizers and bio-inoculants, have been shown to improve growth, yield and nutrient uptake and soil fertility status (4, 5). The economic impact of black gram cultivation is substantial, contributing approximately ₹15000 crores to India's agricultural economy annually (2). Alkaline soils, which constitute about 42 % of India's arable land, significantly hinder black gram cultivation due to their high pH and calcium carbonate content, leading to physiological disorders such as stunted growth and reduced nodulation, ultimately causing yield reductions of up to 30 % (6, 7).

Under alkaline conditions, zinc (Zn) undergoes significant transformations that affect its availability to plants. Zn primarily forms hydroxides such as zinc hydroxide, which precipitate in alkaline soils, leading to strong adsorption onto soil particles and reduced bioavailability for plant uptake (8, 9). Additionally, Zn can form complexes with calcium carbonate, further immobilizing it and rendering it less accessible to plants (8). The adsorption characteristics of Zn are influenced by various soil properties, including pH, organic carbon content and cation exchange capacity, which collectively determine its retention and mobility in the soil (10, 11). Zinc deficiency in calcareous alkaline soils significantly hampers black gram growth as evidenced by the drop in DTPA-extractable zinc levels below the critical threshold of 1.0 ppm necessary for optimal development (12, 13). Zinc deficiency is a prevalent constraint in alkaline soils affecting pulse productivity. Pulse crops (black gram) often shows reduced yields in such conditions. While zinc supplementation through fertilizers is common, the combined use of organic and inorganic zinc source will enhance zinc availability to crop.

Zinc deficiency in alkaline soils can be managed through an integrated approach that combines the application of zinc sulphate ($ZnSO_4$) and zinc solubilizing bacteria (ZSB). The application of $ZnSO_4$ at 25 kg/ha significantly enhances zinc availability, increasing DTPA-extractable zinc from 0.3 to 1.2 ppm, which is crucial for plant health and productivity (12). Chemical fertilization alone often fails to maintain sustained zinc availability due to rapid fixation in alkaline soils. The integration of ZSB strains, such as *Bacillus aryabhattai* and *Pseudomonas aeruginosa*, as these microorganisms utilize various mechanisms to solubilize zinc, including the production of organic acids that lower rhizosphere pH, synthesis of chelating compounds and secretion of siderophores, which facilitate nutrient uptake by plants (13, 14). Studies indicate that this synergistic approach can increase zinc uptake by approximately 40– 45 % and boost grain yield by 20–25 % due to improved nutrient availability and plant physiological responses, including enhanced flowering and pod development (15–17). The role of ZSB in solubilizing zinc from soil and facilitating its absorption by plants is critical, especially in zinc-deficient soils, which are prevalent in many agricultural regions (18, 19). This strategy not only addresses micronutrient malnutrition in crops but also contributes to improved food security and human health by increasing the nutritional quality of staple crops (17). This study aims to quantify the synergistic effects of chemical and biological zinc management strategies on DTPA-extractable zinc levels, plant growth parameters and grain yield of black gram.

Materials and Methods

The current experimental study was conducted on black gram, variety Vamban 8 at two different locations namely, Agricultural College and Research Institute (AC & RI), Madurai and Coastal Saline Research Centre (CSRC), Ramanathapuram during January 2022 using a randomized block design (RBD) with 3 replications. Each replication was divided into 8 treatments, resulting in 24 plots as mentioned below. The sowing was taken up on 24.12.2021 and 07.01.2022 at CSRC, Ramanathapuram and at AC & RI, Madurai respectively. Harvesting was done during 02.03.2022 and 09.03.2022 at CSRC, Ramanthapuram. At AC & RI, Madurai, harvesting was taken up during 14.03.2022 and 18.03.2022.

Before the experimentation, soil samples were collected at random places at 0–15 cm depth across the experimental site and made into single composite. The composite soil sample was processed and used for analysis of physico-chemical characteristics viz., textural fraction (International pipette method), bulk density (Core sampler method), particle density (Core sampler method), soil reaction (pH), Electrical Conductivity (EC), soil organic carbon (Dichromate wet digestion method), available nitrogen (Alkaline permanganate method), available phosphorus (Olsen method), available potassium (Neutral normal NH4OAc method), DTPA - extractable Zn, Fe, Cu, Mn (Atomic Absorption Spectrophotometer). Three plants from each plot were tagged and utilized for recording biometric observations of growth attributes (plant height, shoot and root length, number of root nodules per plant) and yield attributes (number of pods plant^{-1}, number of seeds pod^{-1} and seed yield). The data collected were statistically analyzed using AGRES software package.

Following treatments were studied,

T1 -	No $ZnSO_4$ (NPK alone)
T2 -	Zinc Solubilizing Bacteria (ZSB) alone @ 500 mL/ha
T3 -	12.5 kg $ZnSO_4$ ha^{-1}
T4 -	12.5 kg $ZnSO_4$ ha^{-1} + ZSB @ 500 mL/ha
T5 -	18.75 kg $ZnSO_4$ ha^{-1}
T6 -	18.75 kg $ZnSO_4$ ha^{-1} + ZSB @ 500 mL/ha
T7 -	25 kg $ZnSO_4$ ha^{-1}
T8 -	25 kg $ZnSO_4$ ha^{-1} + ZSB @ 500 mL/ha

Results and Discussion

Initial soil characteristics

The study was done in alkaline soil with initial soil characteristics tabulated below (Table 1). The physical and chemical properties of the soils revealed that both AC & RI MDU and CSRC RMD have alkaline soils, with pH values of 8.52 and 8.68 respectively. Electrical conductivity (EC) was low, measuring 0.48 dS m^{-1} at AC & RI MDU and 0.26 dS m^{-1} at CSRC RMD, indicating non-saline conditions. Organic carbon (OC) content was moderate, with AC & RI MDU having 5.2 g kg^{-1} compared to 2.8 g kg^{-1} at CSRC RMD. Bulk density values were 1.38 mg m^{-3} for AC & RI MDU and 1.52 mg m^{-3} for CSRC RMD, suggesting slightly denser soil at CSRC RMD. The analysis of available nutrients indicates that soils from AC & RI MDU have higher available nitrogen (220 kg ha^{-1}), potassium (360 kg ha^{-1}) and DTPA-extractable zinc (0.62 ppm) compared to CSRC RMD, which recorded 146 kg ha^{-1}, 245 kg ha^{-1} and 0.29 ppm respectively. Available phosphorus was comparable at both centres, with 22.5 kg ha^{-1} at AC & RI MDU and 24 kg ha^{-1} at CSRC RMD. Cation exchange capacity (CEC) was higher at AC & RI MDU (18.5 C mol (p$^+$)/kg) than CSRC RMD (14.6 C mol (p$^+$)/kg), while exchangeable sodium was slightly elevated at AC & RI MDU (2.4 meq/100 g soil) compared to CSRC RMD (2.2 meq/100 g soil). The exchangeable sodium percentage (ESP) was 15.1 at AC & RI MDU and 16.3 at CSRC RMD, reflecting moderate levels of sodium influence.

Table 1. Physical and chemical properties of initial soil samples

Available nutrients	Centers		Physical & chemical properties*	Centers	
	AC & RI MDU	CSRC RMD		AC & RI MDU	CSRC RMD
Nitrogen (kg ha^{-1})	220	146	pH	8.52	8.68
Phosphorus (kg ha^{-1})	22.5	24	EC (dS m^{-1})	0.48	0.26
Potassium (kg ha^{-1})	360	245	Organic C (g kg^{-1})	5.2	2.8
DTPA Zinc (ppm)	0.62	0.47	Bulk density (mg m^{-3})	1.38	1.52
CEC (C mol(p$^+$)/kg of soil)	18.5	14.6	Exchangeable sodium percentage	12.9	15.1
Exchangeable sodium (meq/100 g soil)	2.4	2.2	Free $CaCO_3$ (%)	10.4	9.3

**Mean of three soil samples initial soil data*

Effect of ZSB and zinc sulphate on growth parameters of black gram

Plant height (cm)

Among the treatments, T8 (NPK + 25 kg ZnSO4 + ZSB at 500 mL ha^{-1}) produced the tallest plants with a height of 29.5 cm at AC & RI, Madurai and 41.2 cm at CSRC, Ramanathapuram. Pooled data (Table 2) also showed the same trend. Application of $ZnSO_4$ at 18.75 kg ha^{-1} and ZSB (500 mL ha^{-1}) along with NPK was equally effective in improving the plant height (28.8 cm) at AC & RI, Madurai and 39.5 cm at CSRC, Ramanathapuram. The plant height of 27.2 cm was recorded when NPK alone (T1) was applied. Application of zinc along with ZSB supply might have contributed to an increased enzymatic activity and auxin metabolism of plants which results in increased plant height. The combined application of ZSB and zinc provides a balanced nutrient supply to the crop, leading to enhanced growth and development. The positive relationship between zinc and nitrogen resulted in increased plant height which could be attributed to the increased uptake of nitrogen which resulted in enhanced photosynthetic activity and chlorophyll synthesis (20).

Shoot length: The perusal of the data (Table 3) shows that the growth parameters including plant height, shoot length, root length and number of root nodules, showed significant variations across different treatments of zinc sulphate ($ZnSO_4$) and zinc solubilizing bacteria (ZSB). The plant growth measurements at different treatment levels demonstrated notable differences among all the applications. The highest shoot length of 38.18 cm was recorded in the treatment T8 (soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{1}), followed by T6 - soil test based NPK along with 18.75 kg $ZnSO_4$+ ZSB (36.98 cm), which was statistically comparable with T7 - soil test based NPK + 25 kg $ZnSO_4$ alone (36.57 cm). The minimal shoot length of 28.05 cm was registered in the control treatment (T1). The positive response observed from the combined application of ZSB and $ZnSO_4$ may be attributed to their distinct roles in shoot morphology, cell division, cell wall plasticity, energy metabolism and enhanced root development, which collectively contribute to improved shoot growth (21, 22). Previous studies revealed that zinc solubilizing bacteria along with inorganic zinc fertilizer might increase the bioavailability of insoluble soil zinc in alkaline soil for plant use by producing organic acids (23, 24). Researchers reported that the mineralization, solubilization and translocation of zinc, facilitated by the production of organic acids and proton extrusion from biofertilizers enhance zinc availability to plants, thereby contributing to improved plant shoot length (25).

Table 2. Effect of ZSB and zinc sulphate on plant height of black gram

Treatments	AC & RI MDU	CSRC RMD	Pooled mean
T1- No $ZnSO_4$	26.5	27.9	27.2
T2 - ZSB	27.8	29.8	28.8
T3 - 12.5 kg $ZnSO_4$	29.0	31.2	30.1
T4 - 12.5 kg $ZnSO_4$ + ZSB	29.8	31.3	30.4
T5 - 18.75 kg $ZnSO_4$	31.1	32.0	31.5
T6 - 18.75 kg $ZnSO_4$ + ZSB	33.5	35.4	34.2
T7 - 25 kg $ZnSO_4$	32.5	34.7	33.6
T8 - 25 kg $ZnSO_4$ + ZSB	34.5	36.3	35.4
SEd	**0.5**	**0.45**	**0.52**
CD (p = 0.05)	**1.0**	**0.9**	**1.05**

Root length (cm): For root length, T8 (soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{-1}) again showed superior results with 10.99 cm, followed by T6 - soil test based NPK along with 18.75 kg $ZnSO_4$+ ZSB with 10.78 cm root length. This was found to be statistically on par with the treatment receiving (Table 3). Soil test based NPK along with 25 kg of $ZnSO_4$(T7) alone with the root length of 10.41 cm. The lowest root length was recorded in control treatment (8.68 cm). The pronounced effect of zinc-solubilizing bacteria combined with inorganic fertilizer on root length can be attributed to zinc's role in promoting root elongation through cell division and enlargement in the root meristematic tissues as well as its involvement in protein and cell wall synthesis, amino acid production. This is in turn enhances root development, facilitating better nutrient and water uptake and strengthens stress tolerance through improved antioxidant activity and membrane stability (25). Similar results have been reported in previous studies (12, 14, 26).

Root nodules : Regarding root nodules, T8 (soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{-1}) demonstrated the best performance with 27.4 nodules per plant, significantly outperforming other treatments. This treatment was followed by T6 treatment supplied with soil test based NPK along with 18.75 kg $ZnSO_4$+ ZSB with nodule count of 26.6 which was found to be statistically on par with T7 (26.0). The progressive improvement in nodulation from T1 (13.9) to T8 (27.4) suggests a positive influence of increasing zinc doses, particularly when combined with ZSB (Table 3). This significant difference was because of the application of zinc sulphate along with ZSB induces enzyme activity, leghemoglobin (an oxygen-carrying phytoglobin) and accelerates various metabolisms which helps in increasing the nodule count in root and also increases the nitrogen fixation (27). An early study reported that the increase in the number of nodules per plant could be attributed to the creation of more favorable conditions for microorganisms or the development of a conducive soil environment for microbial proliferation through the application of bioinoculants in combination with inorganic fertilizers (28).

Table 3. Effect of ZSB and Zinc sulphate on biometric attributes of black gram

Treatments	Shoot length (cm)			Root length (cm)			Root nodules (No.)		
	AC & RI MDU	CSRC RMD	Pooled mean	AC & RI MDU	CSRC RMD	Pooled mean	AC & RI MDU	CSRC RMD	Pooled mean
T1 -No $ZnSO_4$	27.90	28.20	28.05	11.26	6.10	8.68	15.2	12.5	13.9
T2 - ZSB	31.10	30.30	30.70	11.70	6.20	8.95	18.7	13.8	14.9
T3 - 12.5 kg $ZnSO_4$	31.74	33.74	32.74	12.10	6.60	9.35	22.0	19.8	20.9
T4 - 12.5 kg $ZnSO_4$ + ZSB	32.47	32.97	32.72	12.82	6.90	9.86	22.6	20.3	21.5
T5 - 18.75 kg $ZnSO_4$	33.03	35.03	34.03	12.50	7.26	9.88	24.1	22.4	23.3
T6 - 18.75 kg $ZnSO_4$ + ZSB	35.48	38.48	36.98	13.90	7.65	10.78	27.1	25.7	26.6
T7 - 25 kg $ZnSO_4$	35.53	37.60	36.57	13.40	7.42	10.41	26.8	25.1	26.0
T8 – 25 kg $ZnSO_4$ + ZSB	37.10	39.25	38.18	14.08	7.89	10.99	28.3	26.5	27.4
SEd	**0.32**	**0.50**	**0.42**	**0.10**	**0.21**	**0.16**	**0.53**	**0.40**	**0.50**
CD (p = 0.05)	**0.71**	**1.17**	**0.94**	**0.22**	**0.45**	**0.34**	**1.07**	**0.80**	**1.00**

Effect of ZSB and zinc sulphate on yield attributes and seed yield of black gram

Number of pods per plant and number of seeds per pod

Combined application of zinc inorganic fertilizer along with ZSB has significant impact on yield attributes viz., number. of pods per plant, number. of seeds per pod and seed yield. Among the treatments, T8 (soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{-1}) recorded the highest number of pods per plant at 25.45, followed by T6 - soil test based NPK + 18.75 kg $ZnSO_4$ and ZSB (24.75 pods/plant), which was statistically comparable with T7 (23.65 pods/plant). For the number of seeds per pod, T8 (soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{-1}) again showed the best results with 5.7 seeds per pod, followed by T6 with 5.5 seeds per pod (Table 4). The combination of 25 kg $ZnSO_4$ + ZSB also proved to be the most effective for seed yield per hectare. The yield attributes were significantly increased with the application of bioinoculants and inorganic sources by improving the soil physical properties, which provide the favourable conditions for higher nutrient use efficiency. The combined application of ZSB and zinc sulphate facilitated the transition from the somatic to the reproductive phase, boosted auxin synthesis, promoted nodulation and enhanced nitrogen fixation. These factors collectively contributed to improved yield attributes, ultimately leading to an increase in the seed yield of black gram. These results are in accordance with the findings of previous studies (28-30).

Seed yield

Regarding seed yield, T8 (Soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{-1}) showed the best result with 851 kg ha^{-1}, significantly outperforming all other treatments. This was followed by T6 - soil test based NPK + $ZNSO_4$ @ 25 kg ha^{-1} and ZSB @ 500 mL ha^{-1} (832 kg ha^{-1}) and T7- soil test based NPK + $ZNSO_4$ @ 25 kg ha^{-1} (822 kg ha^{-1}), demonstrating the positive impact of higher zinc doses combined with ZSB application. The progressive improvement in yield parameters from T1 to T8 indicated a strong positive correlation between zinc application and crop productivity, particularly when enhanced by ZSB (Table 4). The highest seed yield of the treatments that received mineral fertilizers and bioinoculant might be due to the ability of ZSB to secrete organic acids for solubilization of precipitated zinc (zinc hydroxide) and lowering the pH of the surrounding bulk and rhizosphere soil which creates a favourable environment for higher zinc availability and seed yield (29). Zinc solubilizing bacteria has been found to produce vitamins (Vitamin A, B1, B2, B3, C and E), Indole Acetic Acid (IAA), Naphthalene acetic acid and gibberellin-like compounds. These growth factors, combined with the improved nutritional conditions might have played a significant role on enhancing the grain yield (31, 32, 33). The Fig. 1 shows the yield attributes of black gram.

Effect of ZSB and zinc sulphate on availability of zinc, zinc uptake and zinc use efficiency in black gram

Based on the experimental data analysis, T8 (soil test based NPK + $ZnSO_4$ 25 kg ha^{-1} + ZSB 500 mL ha^{-1}) emerged as the best treatment, recording the highest DTPA Zn (1.72 mg/kg), maximum uptake of zinc (84.73 g/ha), which in return leads to high zinc use efficiency (21.42 kg/kg) in the pooled mean. This was followed byT6 (soil test based NPK + 18.75 kg $ZnSO_4$ + ZSB), which (Fig. 2) showed the second-best performance with available Zn at 1.57 mg/kg, zinc uptake of 80.85 g ha^{-1} and notably and the highest zinc use efficiency (ZUE) of 24.02 kg/kg. The treatment receiving 25 kg $ZnSO_4$ (T7) was found to be statistically on par with T6 in terms of DTPA Zn (1.43 mg/kg) and zinc uptake (77.09 g/ha), as indicated by the CD values at p = 0.05 (DTPA Zn: 0.25, Zn uptake: 2.59). Similarly, T5 (18.75 kg $ZnSO_4$) showed statistical parity with T4 for both DTPA Zn values and zinc uptake parameters (Table 5). Fig. 3 shows ZUE of black gram.

The improved zinc uptake by black gram achieved through the combined application of mineral fertilizers and bioinoculants can be attributed to the release of micronutrients facilitated by the production of organic acids during microbial decomposition. This process likely facilitated the solubilization of insoluble micronutrient compounds in the soil and provided natural chelating agents, making the nutrients more available to the crop. Additionally, the released organic compounds may have prevented zinc fixation, precipitation, oxidation and leaching through their chelating action, thereby increasing zinc uptake by the plants. This observation is in accordance with the findings of previous studies (34-36).

Conclusion

The study highlights the effectiveness of integrated nutrient management on enhancing the crop growth, yield and zinc use efficiency. The conjoint application of $ZnSO_4$ (25 kg ha^{-1}) and ZSB (500 mL ha^{-1}) along with soil test-based NPK resulted in the highest values for plant height (35.4 cm), shoot length (38.2 cm), root length (10.99 cm), number of nodules per plant (27.4),

Table 4. Effect of ZSB and zinc sulphate on yield and yield attributes of black gram

Treatments	No. of pods/ plant			No. of seeds/ pod			Seed yield (kg ha^{-1})		
	AC & RI MDU	CSRC RMD	Pooled Mean	AC & RI MDU	CSRC RMD	Pooled mean	AC & RI MDU	CSRC RMD	Pooled mean
T1- No $ZnSO_4$	24.1	12.5	18.30	5.2	4.1	4.7	805	655	730
T2- ZSB	24.3	12.7	18.50	5.4	4.2	4.8	820	672	746
T3- 12.5 kg $ZnSO_4$	25.3	13.2	19.25	5.8	4.3	5.1	838	691	765
T4 - 12.5 kg $ZnSO_4$ + ZSB	28.6	13.4	21.00	5.7	4.5	5.1	840	719	780
T5 - 18.75 kg $ZnSO_4$	32.4	13.7	23.05	5.7	4.6	5.2	850	726	788
T6 - 18.75 kg $ZnSO_4$ + ZSB	34.9	14.6	24.75	5.9	5.0	5.5	885	779	832
T7 - 25 kg $ZnSO_4$	33.1	14.2	23.65	5.9	4.9	5.4	887	757	822
T8 – 25 kg $ZnSO_4$ + ZSB	35.8	15.1	25.45	6.2	5.2	5.7	898	803	851
SEd	**0.61**	**0.37**	**0.50**	**0.04**	**0.08**	**0.06**	**12**	**18**	**15**
CD (p = 0.05)	**1.43**	**0.80**	**1.12**	**0.16**	**0.17**	**0.17**	**26**	**39**	**33**

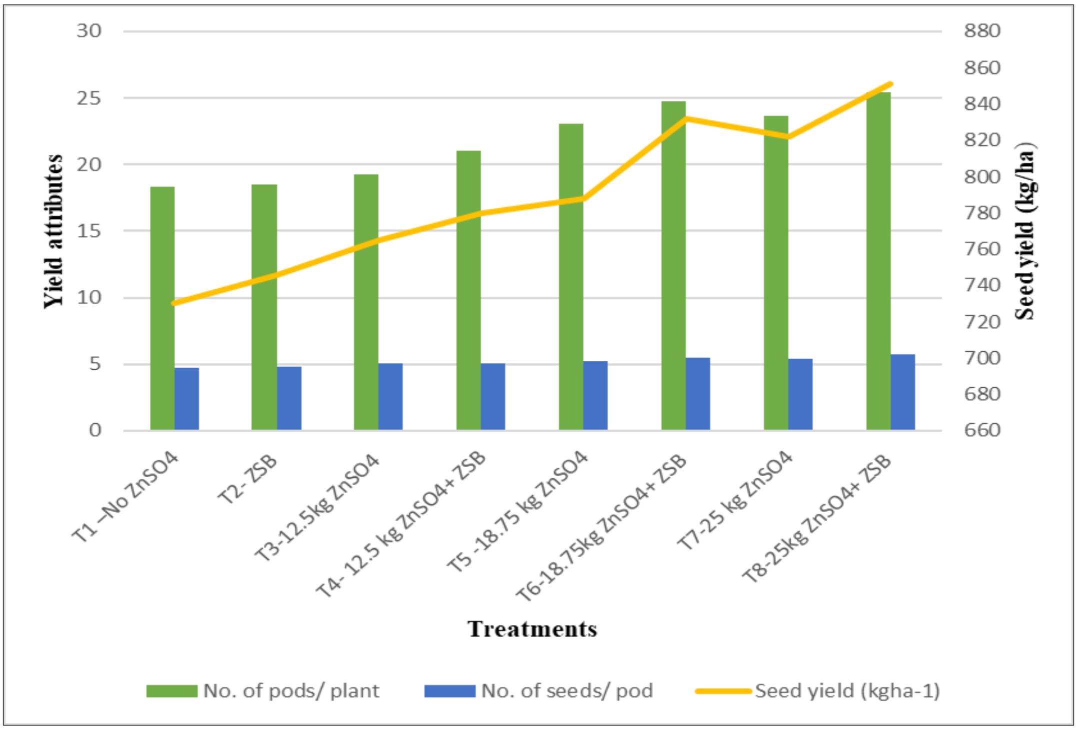

Fig. 1. Yield attributes of black gram.

Table 5. Effect of ZSB and zinc sulphate on availability of zinc, zinc uptake and zinc use efficiency in black gram

Treatments	DTPA Zn (mg kg^{-1})			Zn uptake (g ha^{-1})			ZUE (kg kg^{-1})		
	AC & RI MDU	CSRC RMD	Pooled mean	AC & RI MDU	CSRC RMD	Pooled mean	AC & RI MDU	CSRC RMD	Pooled mean
T1 - No $ZnSO_4$	0.56	0.49	0.36	52.90	50.14	51.52	-	-	
T2 - ZSB	0.58	0.70	0.69	57.40	53.40	55.40	-	-	
T3 -12.5 kg $ZnSO_4$	0.65	1.10	0.84	63.70	64.10	63.90	9.71	10.47	10.09
T4 - 12.5 kg $ZnSO_4$ + ZSB	0.83	1.20	1.02	67.33	65.33	66.33	10.47	21.14	15.80
T5 - 18.75 kg $ZnSO_4$	1.01	1.59	1.30	71.13	76.21	73.67	9.66	16.02	12.84
T6 - 18.75 kg $ZnSO_4$ + ZSB	1.44	1.70	1.57	82.06	79.63	80.85	18.44	29.61	24.02
T7 - 25 kg $ZnSO_4$	1.22	1.64	1.43	76.03	78.15	77.09	14.19	17.80	15.99
T8 - 25 kg $ZnSO_4$ + ZSB	1.56	1.87	1.72	85.26	84.19	84.73	16.28	26.57	21.42
SEd	**0.15**	**0.11**	**0.13**	**1.41**	**1.23**	**1.32**			
CD (p = 0.05)	**0.29**	**0.21**	**0.25**	**2.49**	**2.69**	**2.59**			

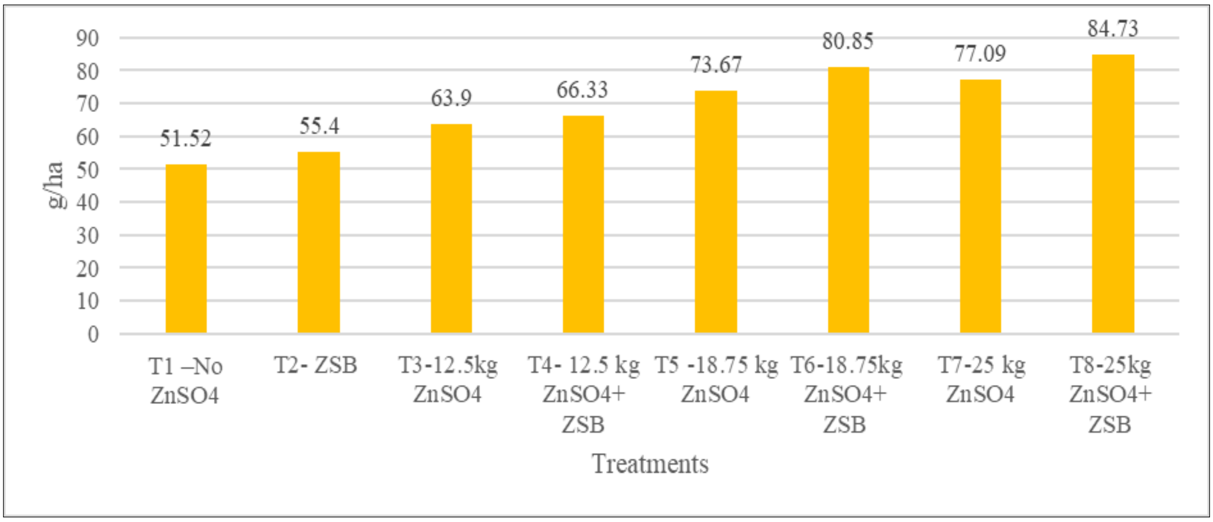

Fig. 2. Zinc uptake of black gram.

number of pods per plant (25.5), number of seeds per plant (5.7) and seed yield (851 kg ha^{-1}). This treatment also significantly improved zinc dynamics, showing higher DTPA-Zinc availability (0.88 mg kg^{-1}) and zinc uptake (79.2 g ha^{-1}). The second-best performance was observed with the application of $ZnSO_4$ (18.75 kg ha^{-1}) and ZSB (500 mL ha^{-1}), which achieved slightly lower values across these parameters. Notably, zinc use efficiency was markedly influenced by the integration of ZSB with $ZnSO_4$, but substantially decreased with higher fertilizer dosages, emphasizing the importance of balanced nutrient management strategies. These results demonstrate that combining biological inputs like ZSB with optimized $ZnSO_4$ dosages not only maximizes crop performance but also ensures sustainable nutrient utilization.

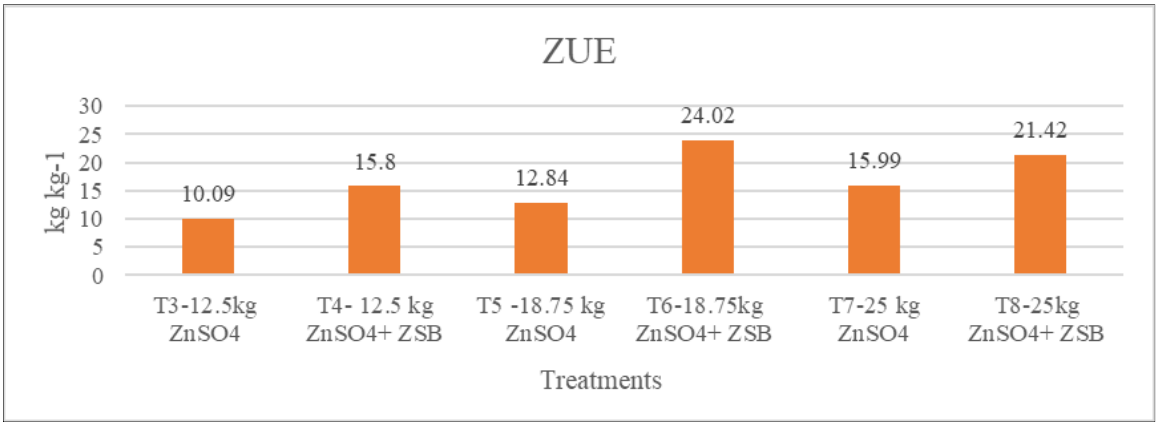

Fig. 3. Zinc use efficiency of black gram.

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Authors' contributions

All authors made equal contribution in the present research.

Compliance with ethical standards

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

Ethical issues : None

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