AATCC Review

21 June 2025: Received
09 August 2025: Revised
17 August 2025: Accepted
16 September 2025: Available Online

https://aatcc.peerjournals.net/

Original Research Article
Open Access

Effect of zinc-enriched organic manures on zinc composition in wheat and zinc pools in a vertisols of central India

Sangya Singh, G. S. Tagore*, Shubham Singh and Shailu Yadav

Department of Soil Science and Agricultural Chemistry, Jawaharlal Nehru Krishi Vishwa Vidhyalaya Jabalpur, Madhya Pradesh, 482004, India

ABSTRACT

Aim: *The study was conducted at Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, Madhya Pradesh, India, to evaluate the effect of zinc-enriched organic manures on wheat yield, zinc uptake, and the distribution of zinc pools in soil. The research aimed to identify integrated nutrient management strategies that enhance wheat productivity and micronutrient availability in zinc-deficient soils.*

Methods: *A pot experiment was conducted to assess the impact of various combinations, organic manures (farm yard manure (FYM), Vermicompost (VC), and Poultry manure (PM)), Zinc (Zn), and Zinc-Solubilizing Bacteria (ZSB). For enrichment: incubation of 10 t FYM, 5 t VC, and 2.5 t PM ha^{-1} with Zn at 2.5 or 5.0 kg ha^{-1}, and with or without ZSB. Parameters chlorophyll content (SPAD and pigment concentration), yield attributes, and nutrient uptake by wheat, were recorded. The soil nutrient availability, DTPA-extractable micronutrients, and pools of Zn were assessed.*

Results: *The results indicated that the application of 10 t ha^{-1} enriched FYM with 5.0 kg Zn ha^{-1} and ZSB (Pseudomonas aeruginosa) showed the highest SPAD reading (40), chlorophyll "a" (1.15 mg g^{-1}), chlorophyll "b" (0.67 mg g^{-1}), total chlorophyll (1.82 mg g^{-1} at 35 DAS), spike length (7.53 cm), number of grains (19) spikelets^{-1}, grain weight (2.90 g pot^{-1}), dry matter production (11.18 g pot^{-1}) and Zn content and uptake by wheat. Zn-enriched poultry manure enhanced Zn and Cu availability, while Zn-enriched farm yard manure significantly improved soil NPK content and micronutrient availability. Application of enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB showed the highest uptake of Cu and Mn, while enriched poultry manure with 5.0 kg Zn ha^{-1} recorded the highest Fe uptake.*

Conclusion: *The application of enriched organic manures (FYM, VC, and PM) with Zn and ZSB significantly increased the availability and uptake of Zn, Cu, Fe, and Mn by wheat. Application of 2.5.0 t ha^{-1} enriched poultry manure with 5.0 kg Zn ha^{-1} and 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB were particularly effective in increasing total and plant-available Zn pools in the soil. The findings highlight the importance of enrichment of organic manures with Zn and ZSB in improving micronutrient bioavailability, sustaining soil fertility, and enhancing wheat productivity in zinc-deficient soils.*

Keywords: *Zinc, Enriched Organic manures, ZSB, Wheat, Zinc pools, Uptake..*

Introduction

Zinc (Zn) is an essential micronutrient required for the cellular, physiological, and biological development of plants, animals, and humans [5]. It serves as a cofactor for over 300 enzymes and is vital for processes such as DNA and protein synthesis, carbohydrate metabolism, gene expression, enzyme activation, photosynthesis, hormone production, disease resistance, wound healing, and fertility [16].

Despite its importance, zinc deficiency is the most widespread micronutrient limitation in soils globally [27]. This deficiency impairs critical biological functions, resulting in reduced crop yields and lower zinc concentrations in edible plant parts [4]; [12]. Zinc uptake occurs primarily in the rhizosphere, and insufficient zinc in this zone leads to poor accumulation in grains and fruits [18]. Over half of the world's cereal-growing soils are affected by zinc deficiency.

Corresponding Author: **G. S. Tagore*

DOI: https://doi.org/10.21276/AATCCReview.2025.13.04.430

To address this, several strategies have been explored to enhance zinc bioavailability in soils. Zinc sulphate ($ZnSO_4$) is widely used due to its high solubility; however, its effectiveness is often limited by rapid fixation in the soil [10]. Alternatively, zinc-solubilizing bacteria (ZSB) have shown promise in mobilizing unavailable forms of zinc into plant-accessible forms, thereby improving zinc uptake and enhancing crop yields [22]; [11]. The use of ZSB as biofertilizers has been successfully demonstrated in wheat cultivation [14]; [9]. Another promising approach is the enrichment of organic manures with micronutrients. These organo-metallic complexes prevent nutrient fixation, increase zinc and iron availability in the root zone, and improve nutrient use efficiency while reducing reliance on inorganic fertilizers [10]. Enriched organic manures also enhance soil fertility with smaller application rates. Given these potential benefits, the study aimed to evaluate the impact of zinc-enriched organic manures on chlorophyll content, yield attributes, zinc uptake by wheat, and zinc availability in Vertisol soils.

Materials and Methods

Description of experiment

The study was conducted during 2018-2020 at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, JNKVV, Jabalpur.

Organics, *viz.,* fresh cow and buffalo dung, FYM, and vermicompost were sourced from the Dairy Unit of JNKVV Jabalpur. Poultry manure obtained from Nanaji Deshmukh Veterinary University, Jabalpur. The ZSB strain of *Pseudomonas aeruginosa* was obtained from MRPC, JNKVV, Jabalpur. These organic materials were incubated with $ZnSO_4.7H_2O$ at varying zinc concentrations (0, 1.1, and 2.2 mg Zn/kg) for 90 days, along with a zinc-solubilizing bacterial inoculant. A glasshouse experiment was then conducted on wheat (GW-366) in pots arranged in a Completely Randomized Design (CRD) with three replications. The treatments applied to the soil (4 kg pot^{-1}) were :

T0: Control
T1: FYM @ 10 t ha^{-1}
T2: Vermicompost @ 5 t ha^{-1}
T3: Poultry manure @ 2.5 t ha^{-1}
T4: FYM @ 10 t ha^{-1} + Zn @ 5 kg ha^{-1}
T5: Vermicompost @ 5 t ha^{-1} + Zn @ 2.5 kg ha^{-1}
T6: Poultry manure @ 2.5 t ha^{-1} + Zn @ 5 kg ha^{-1}
T7: FYM @ 10 t ha^{-1} + Zn @ 5 kg ha^{-1} + ZSB
T8: Vermicompost @ 5 t ha^{-1} + Zn @ 5 kg ha^{-1} + ZSB
T9: Poultry manure @ 2.5 t ha^{-1} + Zn @ 2.5 kg ha^{-1} + ZSB

Nutrient content in organic manures and supplied pot^{-1}

The nutrient content and supply from different organic manures vary significantly. Farmyard manure (FYM) contains 0.43% nitrogen (N), 0.23% phosphorus (P), 0.38% potassium (K), and 116 mg kg^{-1} of zinc (Zn), supplying 0.089 g of N, 0.022 g of P, 0.089 g of K, and 0.064 mg of Zn pot^{-1}. Vermicompost, with a higher nutrient concentration, contains 2.01 % N, 1.10 % P, 1.20% K, and 65 mg kg^{-1} of Zn, delivering 0.174 g N, 0.129 g P, 0.103 g K, and 0.005 mg Zn pot^{-1}. Poultry manure shows the highest nutrient content, with 2.42% N, 1.58% P, 1.67% K, and 177 mg kg^{-1} Zn, supplying 0.2 g N, 0.11 g P, 0.085 g K, and 0.02 mg Zn pot^{-1}. Thus, poultry manure and vermicompost provide comparatively higher macro-nutrient levels, while FYM contributes a greater amount of zinc pot^{-1}.

Management of the crop

The fifteen seeds were sown in each of the pots on December 15, 2019. The amounts of fertilizer were calculated for each pot based on a soil weight of 2.26 x 10^6 kg per hectare. The basal fertilizer doses included 120 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} applied as urea, diammonium phosphate (DAP), and muriate of potash (MoP), respectively. Zinc was applied as zinc sulfate ($ZnSO_4.7H_2O$). The amounts applied per pot were 376 mg of N, 232 mg of P_2O_5, 119 mg of K_2O, and an appropriate quantity of Zn. Organics were also added: farmyard manure (FYM) at 17.85 g pot^{-1}, vermicompost at 8.92 g pot^{-1}, and poultry manure at 4.46 g pot^{-1}. Five plant pot^{-1} were selected for observation and analysis of wheat yield and related attributes. The crop was harvested in April 2020. Chlorophyll content was measured in the 4^{th} and 5^{th} leaves from the top using a SPAD meter at 30 days after sowing (DAS), and at 45 and 90 DAS by the acetone extraction method. Yield attributes such as spike length (cm) and number of grains $spikelet^{-1}$, plant biomass produced pot^{-1} were expressed in g pot^{-1}.

Plant and soil analysis

Zinc content in plant samples was determined after digestion with hydrofluoric (HF) and perchloric acid ($HClO_4$), following the procedure outlined by Jackson [13]. The zinc concentration was then estimated using an atomic absorption spectrophotometer (AAS, Varian 240FS).

Soil samples were analyzed for pH and electrical conductivity (EC) according to the methods described by Jackson [13]. Organic carbon content in the soil was determined using the wet oxidation method, as outlined by Walkley and Black [30]. Soil available N was estimated using the method of Subbiah and Asija [28], available phosphorus was determined by Olsen's method, and available potassium was measured using the 1N ammonium acetate method at pH 7.0. Available zinc was analyzed using an atomic absorption spectrophotometer as described by Lindsay and Norvell [17]. The zinc pools in the soil, including water-soluble, easily exchangeable, complexed, organically bound, zinc bound to carbonate and amorphous oxides (acid-soluble), and zinc bound to crystalline oxides (CBD-extractable), were determined through sequential extraction following the procedure outlined by Edward Raja and Iyengar [7].

Statistical analysis

Standard statistical procedures were employed for analysis and interpretation of data. A pot experiment was done in CRD using 10 treatments and three replications.

Results and Discussion

Physiological and agronomic traits

The results given in Table 1 and depicted in Fig.1 and 2 indicated that the application of 10 t ha^{-1} enriched FYM with 5.0 kg Zn ha^{-1} + Zinc Solubilizing Bacteria (ZSB) resulted in the highest, both in terms of SPAD readings (40.00), chlorophyll concentration (Chl "a" =1.15 mg g^{-1}, Chl "b" =0.67 mg g^{-1}, total =1.82 mg g^{-1} at 35 DAS).The synergistic effect enhanced photosynthetic efficiency (Cakmak and Kutman, 2018). This treatment also recorded the highest spike length (7.53 cm), number of grains (19) $spikelets^{-1}$, grain weight (2.90 g pot^{-1}), and dry matter production (11.18 g pot^{-1}). Similarly, application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1} also showed a significant increase in chlorophyll content and yield attributes. This increase might be explained by the role of zinc in regulating enzyme activation and hormone regulation, which are essential for flower and seed development [16]; [11]. ZSB can solubilize insoluble zinc compounds in the soil, making them more accessible to plants and thereby enhancing the overall nutrient status [9];[8]. Similar results have been reported by [6]; [15], [14], [12]and [29].

Micronutrient content and uptake in wheat

Zn content and uptake

The data in Tables 2 and 3 and Figs 3 and 4 revealed that the highest zinc concentration in both grain (36.02 mg kg^{-1}) and straw (14.39 mg kg^{-1}), along with the highest uptake (104.16 µg pot^{-1} by grain and 119.07 µg pot^{-1} by straw, total 223.24 µg pot^{-1}), was recorded with application of @ 10.0 t ha^{-1} FYM enriched with 5.0 kg Zn ha^{-1} and ZSB. This was followed by application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1}, which recorded grain and straw Zn contents of 34.06 mg kg^{-1} and 13.46 mg kg^{-1}, respectively. In contrast, the control showed lower uptake of 64.94 µg pot^{-1} (28.42 µg pot^{-1} by grain and 36.53 µg pot^{-1} by straw). The substantial increase might be attributed to the synergistic interaction of applied zinc and ZSB, which enhanced Zn bioavailability in the rhizosphere by converting it into more soluble forms [26]; [2]; [22]; [14].

Cu content and uptake

The highest Cu concentration in grain (7.43 mg kg^{-1}) and straw (7.22 mg kg^{-1}) was observed with PM @ 2.5 t ha^{-1} enriched with Zn @ 2.5 kg ha^{-1} and ZSB. Meanwhile, application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1} and ZSB showed the highest total Cu uptake (79.58 µg pot^{-1}), with 18.55 µg pot^{-1} by grain and 61.02 µg pot^{-1} by straw. This was significantly higher than the control, which recorded a total uptake of 22.54 µg pot^{-1}. The enhanced uptake of Cu is likely due to improved soil structure and microbial activity induced by organic matter and ZSB, which increase micronutrient availability [16].

Fe content and uptake

Application of 2.5 t ha^{-1} poultry manure enriched with 5.0 kg Zn ha^{-1} showed the highest Fe concentration in grain (55.52 mg kg^{-1}) and straw (196.97 mg kg^{-1}), and total Fe uptake (1323.90 µg pot^{-1}), with 76.69 µg pot^{-1} by grain and 1247.21 µg pot^{-1} by straw. The improved Fe uptake is associated with the combined application of zinc and organic amendments, which enhances Fe solubility and mobility in the soil.

Mn content and uptake

Maximum Mn content was recorded with the application of 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB (36.22 mg kg^{-1} in grain and 29.82 mg kg^{-1} in straw), with a total uptake of 241.08 µg pot^{-1} (50.91 µg pot^{-1} by grain and 190.17 µg pot^{-1} by straw). Application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1} and ZSB also showed high Mn uptake, totaling 292.23 µg pot^{-1}. The enhanced Mn uptake can be linked to the combined influence of organic matter, Zn application, and microbial activity, which together improve Mn availability in the rhizosphere by modifying soil pH and stimulating microbial-mediated nutrient solubilization [9], [1].

Soil fertility status as influenced by different treatments

The results from Table 4 clearly indicated that the pH of the soil slightly decreased in enriched treatments, with the lowest observed with application of 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB (6.58), suggesting a mild acidifying effect beneficial for nutrient availability. Organic carbon (OC) content showed enhancement, with application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1} and ZSB (9.10 g kg^{-1}), indicating increased microbial activity and organic matter buildup. Major nutrients N, P, and K were substantially higher in treated plots, with application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1} and ZSB (332.50 kg N ha^{-1}, 40.50 kg P ha^{-1}), and application of 2.5.0 t ha^{-1} enriched poultry manure with 5.0 kg Zn ha^{-1} (375 kg K ha^{-1}) showing the most pronounced effects. Additionally, DTPA-extractable micronutrients were significantly elevated in treatments with Zn and ZSB. Application of 10 t ha^{-1} enriched farm yard manure with 5.0 kg Zn ha^{-1} and ZSB recorded the highest Zn (2.68 mg kg^{-1}), followed by T8 and 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB, illustrating the effectiveness of ZSB in enhancing Zn availability. Fe and Mn levels were also highest in 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB, suggesting improved micronutrient solubility due to organic acids produced during manure decomposition. Among all treatments, FYM enriched with 5 kg Zn ha^{-1} and ZSB consistently outperformed others in improving soil fertility, demonstrating the synergistic benefits of combining organic manures with Zn and ZSB. This integrated nutrient management approach appears promising for enhancing soil health and sustaining crop productivity.

The application of zinc-enriched manures significantly increased the DTPA-extractable iron status of the soil [10] [3]. The release of micronutrients from organic manures makes them more available, as noted by [19], [20]. These results align with the findings of [21], [23].

Zinc pools in soil as influenced by different treatments

The results (Table 5) revealed that treatments with organic manure, zinc application, and ZSB significantly enhanced total and available Zn content in the soil. Application of enriched 2.5 t ha^{-1} poultry manure with 2.5 kg Zn ha^{-1} and ZSB and 10 t ha^{-1} FYM enriched with 5.0 kg Zn ha^{-1} and ZSB recorded the highest total Zn concentrations (110.12 and 98.80 mg kg^{-1}, respectively), significantly higher than the control (71.93 mg kg^{-1}). Residual-Zn formed the dominant Zn pool across all treatments, contributing approximately 80-90% of total Zn. Application of 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB showed the highest Res-Zn value (98.18 mg kg^{-1}) compared to the control (66.19 mg kg^{-1}). Despite being less bioavailable, this pool acts as a long-term Zn reservoir. The increase is attributed to the combined effect of Zn fertilizers, organic amendments, and microbial activity, aligning with the findings of [27] further noted that Zn-enriched organic amendments could form organo-metallic complexes, reducing fixation and increasing Zn availability over time [25], [31].

Labile Zn pools: Water soluble+ exchangeable Zn were increased significantly with application of 2.5.0 t ha^{-1} enriched poultry manure with 5.0 kg Zn ha^{-1} (1.81 mg kg^{-1}) and application of 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB (1.80 mg kg^{-1}), compared to the control (0.57 mg kg^{-1}). These labile forms are the most readily available to plants. Complexed Zn content was highest in the application of 2.5.0 t ha^{-1} enriched poultry manure with 5.0 kg Zn ha^{-1} (2.51 mg kg^{-1}), followed by the application of 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB (2.36 mg kg^{-1}) and T3 (2.08 mg kg^{-1}), compared to the control (0.76 mg kg^{-1}). The increase is likely due to enhanced cation exchange capacity (CEC) and the chelating action of organic compounds, such as humic and fulvic acids, which possess functional groups (OH, COOH, SH, C=O) with strong affinity for Zn. Amorphous sesquioxide-bound Zn increased from 0.89 mg kg^{-1} (control) to 1.62 mg kg^{-1} in FYM 10 t ha^{-1} and 2.20 mg kg^{-1} in PM (2.5.0 t ha^{-1}). The highest value (2.51 mg kg^{-1}) was observed with application of 2.5.0 t ha^{-1} enriched poultry manure with 5.0 kg Zn ha^{-1}. Organic acids released during decomposition likely facilitated Zn dissolution and adsorption onto amorphous sesquioxides. This is due to the high surface area and Zn adsorption capacity of amorphous oxides. Crystalline sesquioxide-bound Zn was significantly higher with the application of 2.5.0 t ha^{-1} enriched poultry manure with 5.0 kg Zn ha^{-1} (6.76 mg kg^{-1}) and application of 2.5 t ha^{-1} enriched poultry manure with 2.5 kg Zn ha^{-1} and ZSB (6.99 mg kg^{-1}) compared to the control (3.53 mg kg^{-1}). A maximum value (7.28 mg kg^{-1}) was recorded in enriched PM with Zn @2.5 kg ha^{-1} and ZSB. The increased CSB-Zn is attributed to higher Zn application, interaction with crystalline iron oxides, and specific adsorption on positively charged mineral surfaces like goethite and gibbsite [11]. Enrichment of organic manures with Zn and ZSB significantly enhanced both total and available Zn pools. These treatments increased the proportion of Zn in more labile and plant-available forms (WSEx-Zn, Comp-Zn, ASB-Zn, CSB-Zn), shifting Zn distribution away from unavailable residual forms. The synergistic effect of organic matter and microbial activity (ZSB) improved Zn solubility and mobility.

Table 1: Chlorophyll content in leaves, yield attributes and yield of wheat as influenced by enriched organic manures with Zinc and ZSB

Treatment	SPAD	Chlorophyll (mg g^{-1}) fresh leaves						Yield attributes		Grain weight (g) pot^{-1}	DMP (g) pot^{-1}
	35DAS	45DAS			90DAS			Spike length (cm)	No of grains Spikelet^{-1}		
		Chl"a"	Chl"b"	Total	Chl"a"	Chl"b"	Total				
T0-Control	30.50	0.45	0.37	0.82	0.39	0.29	0.68	5.13	10.00	1.26	6.07
T1-FYM (10.0 t ha^{-1})	31.00	0.97	0.59	1.51	0.85	0.37	1.22	6.10	12.00	1.32	7.70
T2-VC (5.0 t ha^{-1})	35.30	0.89	0.41	1.31	0.90	0.34	1.24	6.79	14.00	1.60	8.64
T3-PM (2.5.0 t ha^{-1})	31.00	0.60	0.36	0.97	0.49	0.21	0.71	5.26	11.00	1.38	7.17
T4-FYM (10 t ha^{-1}) +5.0 kg Zn ha^{-1}	38.20	1.11	0.67	1.70	1.06	0.53	1.59	7.17	17.00	2.63	9.83
T5-VC (5 t ha^{-1}) +2.5 kg Zn ha^{-1}	36.50	1.04	0.56	1.60	0.81	0.56	1.37	6.68	15.00	1.86	8.78
T6-PM (2.5.0 t ha^{-1})+5.0 kg Zn ha^{-1}	32.67	0.84	0.52	1.36	0.84	0.36	1.20	5.56	13.00	1.38	7.72
T7-FYM (10.0 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	40.00	1.15	0.67	1.82	1.11	0.62	1.73	7.53	19.00	2.90	11.18
T8-VC (5 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	37.73	1.04	0.60	1.65	1.00	0.59	1.59	6.93	16.00	2.18	8.90
T9-PM (2.5 t ha^{-1}) +2.5 kg Zn ha^{-1}+ZSB	33.97	0.95	0.61	1.56	0.99	0.43	1.42	5.86	14.00	1.41	7.78
SEm±	***0.876***	***0.039***	***0.026***	***0.047***	***0.026***	***0.023***	***0.034***	***0.846***	***1.976***	***0.246***	***1.268***
CD (P=0.01)	***3.525***	***0.158***	***0.105***	***0.191***	***0.106***	***0.095***	***0.139***	***7.880***	***8.420***	***8.050***	***8.890***

Table 2: Effect of enriched organic manures with Zinc and ZSB on micronutrient content in wheat

Treatment	Micronutrient content (mg kg^{-1})							
	Zn		Cu		Fe		Mn	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
T0-Control	22.53	7.54	3.95	3.67	36.08	155.73	24.78	18.63
T1-FYM (10.0 t ha^{-1})	25.22	9.74	4.33	4.98	38.57	223.05	22.43	24.53
T2-VC (5.0 t ha^{-1})	28.15	10.17	4.57	3.68	48.00	144.63	20.33	15.37
T3-PM (2.5.0 t ha^{-1})	27.67	8.75	6.26	5.33	49.00	179.33	17.00	20.00
T4-FYM (10 t ha^{-1})+5.0 kg Zn ha^{-1}	34.06	13.46	6.35	6.57	50.97	231.84	25.60	26.70
T5-VC (5 t ha^{-1})+2.5 kg Zn ha^{-1}	31.74	11.68	5.18	4.15	49.87	161.68	25.50	16.48
T6-PM (2.5.0 t ha^{-1})+5.0 kg Zn ha^{-1}	28.85	9.22	7.93	5.92	55.52	196.97	34.17	25.10
T7-FYM (10.0 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	36.02	14.39	6.43	7.35	52.03	252.76	28.90	25.20
T8-VC (5 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	33.59	12.64	5.68	4.48	53.72	166.03	28.43	14.52
T9-PM (2.5 t ha^{-1}) +2.5 kg Zn ha^{-1}+ZSB	29.47	10.40	7.43	7.22	52.43	196.77	36.22	29.82
SEm±	***1.304***	***0.537***	***0.387***	***0.304***	***2.565***	***14.206***	***2.128***	***1.489***
CD (P= 0.01)	***5.249***	***2.160***	***1.556***	***1.224***	***10.321***	***57.163***	***8.564***	***5.992***

Table 3: Uptake of micronutrients by wheat as influenced by enriched organic manures with Zinc and ZSB

Treatments	Uptake of micro-nutrients (µg pot^{-1})											
	Zn			Cu			Fe			Mn		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T0-Control	28.42	36.53	64.94	4.98	17.56	22.54	45.43	703.80	749.23	31.18	89.93	121.11
T1-FYM (10.0 t ha^{-1})	33.20	62.59	95.80	5.71	31.80	37.50	50.78	1429.51	1480.29	29.54	156.73	186.26
T2-VC (5.0 t ha^{-1})	44.99	71.54	116.53	7.29	25.82	33.11	76.65	1018.74	1095.39	32.79	108.71	141.50
T3-PM (2.5.0 t ha^{-1})	38.30	50.81	89.11	8.66	30.63	39.29	67.87	1038.03	1105.90	23.47	115.30	138.77
T4-FYM (10 t ha^{-1}) +5.0 kg Zn ha^{-1}	89.43	96.82	186.26	16.61	47.30	63.91	134.32	1669.68	1804.00	68.07	191.99	260.07
T5-VC (5 t ha^{-1}) +2.5 kg Zn ha^{-1}	58.86	81.08	139.94	9.74	28.51	38.26	93.84	1120.77	1214.62	48.12	112.94	161.06
T6-PM (2.5.0 t ha^{-1}) +5.0 kg Zn ha^{-1}	39.90	58.18	98.07	11.02	37.44	48.46	76.69	1247.21	1323.90	47.29	158.64	205.92
T7-FYM (10.0 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	104.16	119.07	223.24	18.55	61.02	79.58	150.88	2091.64	2242.52	83.51	208.72	292.23
T8-VC (5 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	73.15	86.50	159.65	12.36	30.18	42.54	116.79	1122.77	1239.56	62.00	98.08	160.08
T9-PM (2.5 t ha^{-1}) +2.5 kg Zn ha^{-1}+ZSB	41.53	66.24	107.77	10.46	45.93	56.40	73.83	1260.57	1334.40	50.91	190.17	241.08
SEm±	**2.900**	**6.938**	**6.823**	**0.860**	**2.848**	**3.056**	**7.480**	**95.915**	**96.352**	**5.510**	**12.252**	**15.534**
CD (P=0.01)	**11.670**	**27.918**	**27.456**	**3.480**	**11.459**	**12.296**	**30.090**	**385.954**	**387.715**	**22.160**	**49.301**	**62.506**

Table 4: Effect of enriched organic manures with Zn and ZSB on soil fertility

Treatment	Physicochemical properties			Major nutrients (kg ha^{-1})			DTPA extractable Micronutrients (mg kg^{-1})			
	pH	EC (dSm^{-1})	OC (gkg^{-1})	N	P	K	Zn	Cu	Fe	Mn
T0-Control	7.29	0.18	5.58	258.52	30.43	302	0.45	0.67	8.77	3.86
T1-FYM (10.0 t ha^{-1})	7.36	0.31	8.51	291.66	36.98	347	1.12	0.69	8.34	4.64
T2-VC (5.0 t ha^{-1})	6.97	0.34	8.01	282.04	34.16	303	1.21	0.73	1.00	7.51
T3-PM (2.5 t ha^{-1})	6.65	0.41	7.25	283.75	31.96	367	2.59	0.96	4.76	16.33
T4-FYM (10 t ha^{-1})+5.0 kg Zn ha^{-1}	7.09	0.34	9.56	328.83	40.91	371	1.73	0.64	8.79	6.84
T5-VC (5 t ha^{-1}) +2.5 kg Zn ha^{-1}	7.27	0.38	8.56	301.17	35.58	316	1.12	0.63	10.19	7.24
T6-PM (2.5 t ha^{-1}) +5.0 kg Zn ha^{-1}	6.89	0.37	8.20	286.33	32.07	375	2.68	1.02	6.63	16.43
T7-FYM (10.0 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	7.28	0.37	9.10	332.50	42.50	377	1.48	0.59	8.77	6.18
T8-VC (5 t ha^{-1}) +5.0 kg Zn ha^{-1}+ZSB	7.25	0.33	8.50	303.25	38.10	329	1.27	0.63	10.11	6.42
T9-PM (2.5 t ha^{-1}) +2.5 kg Zn ha^{-1}+ZSB	6.68	0.42	8.01	293.58	34.96	376	2.37	0.99	7.10	17.23
SEm±	***0.182***	***0.024***	***0.442***	***6.940***	***2.121***	***10.432***	***0.088***	***0.032***	***0.428***	***0.461***
CD (P=0.01)	***0.732***	***NS***	***1.780***	***27.927***	***8.536***	***41.979***	***0.355***	***0.130***	***1.721***	***1.854***
Initial	***7.48***	***0.17***	***5.03***	***255.00***	***29.00***	***323.15***	***0.41***	***0.56***	***5.89***	***3.50***

Table 5: Zinc pools and percent contribution as influenced by enriched organic manures with Zinc and ZSB

Treatment	Fractions of zinc in soil (mg kg-1)					
	WSEX-Zn	Comp-Zn	ASB-Zn	CSB-Zn	Residual- Zn	Total Zn
T0-Control	0.57 (0.79)	0.76 (1.05)	0.89 (1.24)	3.53 (4.91)	66.19 (92.01)	71.93 (7.99)
T1-FYM (10.0 t ha^{-1})	0.92 (1.14)	1.57 (1.95)	1.62 (2.01)	5.04 (6.25)	71.45 (88.65)	80.60(11.35)
T2-VC (5.0 t ha^{-1})	0.68 (0.91)	1.26 (1.69)	1.29 (1.74)	4.88 (6.58)	66.00 (89.00)	74.10 (10.93)
T3-PM (2.5 t ha^{-1})	1.55 (1.60)	2.08 (2.15)	2.20 (2.27)	6.26 (6.46)	84.79 (87.52)	96.88 (12.48)
T4-FYM (10 t ha^{-1}) + 5.0 kg Zn ha^{-1}	1.52 (1.62)	1.80 (1.92)	2.07 (2.21)	6.36 (6.78)	82.01 (87.46)	93.76 (12.54)
T5-VC (5 t ha^{-1}) + 2.5 kg Zn ha^{-1}	0.79 (0.95)	1.46 (1.77)	1.65 (2.00)	5.21 (6.31)	73.37 (88.96)	82.48 (11.04)
T6-PM (2.5 t ha^{-1}) + 5.0 kg Zn ha^{-1}	1.81 (1.67)	2.51 (2.32)	2.51 (2.32)	7.00 (6.46)	94.52 (87.23)	108.36 (12.77)
T7-FYM (10.0 t ha^{-1}) + 5.0 kg Zn ha^{-1}+ZSB	1.56 (1.58)	1.94 (1.96)	2.24 (2.27)	6.69 (6.77)	86.37 (87.42)	98.8 (12.58)
T8-VC (5 t ha^{-1}) + 5.0 kg Zn ha^{-1} + ZSB	1.13 (1.33)	1.72 (2.02)	1.87 (2.19)	5.56 (6.53)	74.96 (87.93)	85.25 (12.07)
T9-PM (2.5 t ha^{-1}) +2.5 kg Zn ha^{-1}+ZSB	1.77 (1.61)	2.36 (2.14)	2.33 (2.11)	7.28 (6.61)	96.38 (87.52)	110.12 (12.48)
SEm±	**0.037**	**0.051**	**0.043**	**0.155**	**2.128**	**2.131**
CD (P=0.01)	**0.151**	**0.207**	**0.174**	**0.625**	**8.564**	**8.577**

Percent contribution value given in parentheses

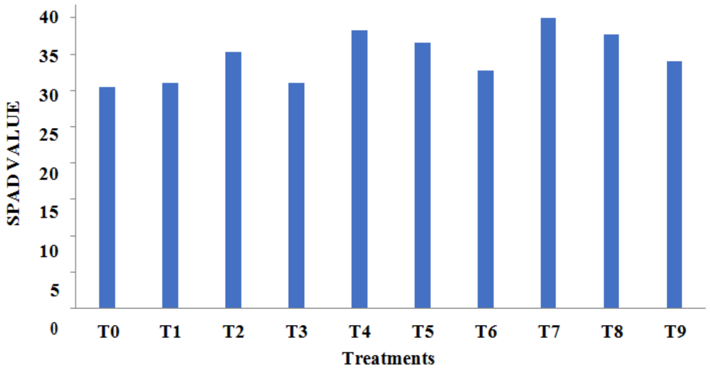

Fig. 1. SPAD reading in fresh leaves of wheat

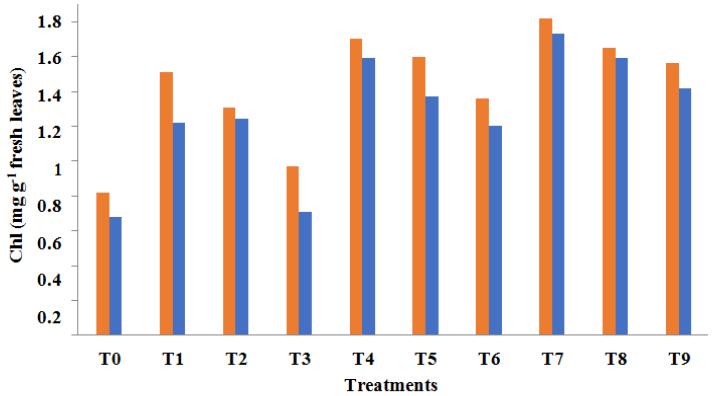

Fig. 2 chlorophyll content in fresh leaves of wheat

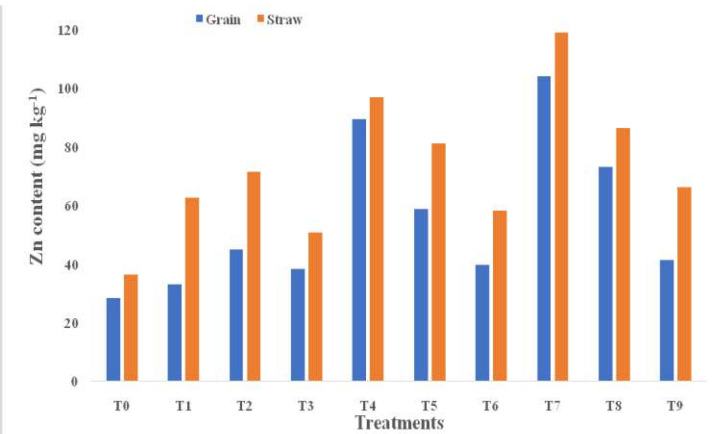

Fig. 3. Zn content in grain and straw of wheat

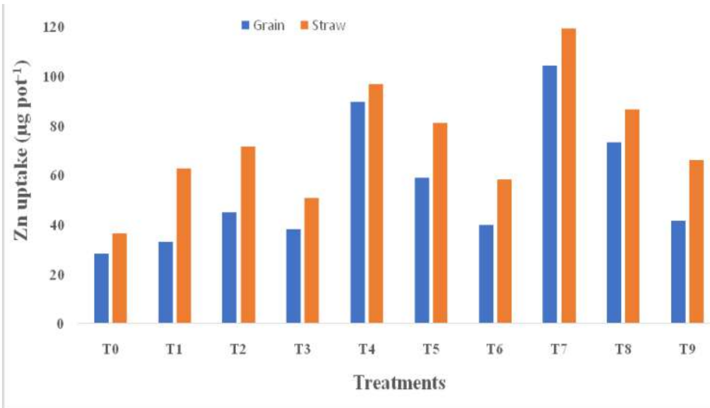

Fig. 4. Zn uptake by grain and straw of wheat

Conclusion

The findings revealed that the application of 10.0 t ha^{-1} enriched FYM with 5.0 kg Zn ha^{-1} and ZSB (*Pseudomonas aeruginosa*) showed a significant increase in the chlorophyll content, yield attributes, and yield, zinc content and uptake, as well as improved soil health. Enriched organic manures with zinc and ZSB application improve the physicochemical properties of the soil, increase the availability of major nutrients and micronutrients, and enhance nutrient uptake by wheat.

References

1. Abbas M, Akmal M, Aziz, I and Rafa H. 2021. Zn ferti-fortification of wheat (*Triticum aestivum* L.) using zinc enriched compost and biochar in rainfed area. Communications in Soil Science and Plant Analysis 52. 1-16.

2. Aketi R, Sharma S, Sharma M, Yadav N, Joshi O. 2014. Inoculation of zinc solubilizing *Pseudomonas aryabhattai* strains for improved growth, mobilization and biofortification of zinc in soybean and wheat cultivated in Vertisols of central India. Applied Soil Ecology73: 87-96.

3. Ali W, Iqbal J, Khalil MK and Ahmad Z.2019.Impact of zinc and organic manure on wheat productivity and soil fertility. Advances in Crop Sciences and Technology 22(2): 131-142.

4. Aziz MA, Ahmad HR, Corwin D, Sabir M, Hakeem K, Ozturk M. 2017. Influence of farmyard manure on retention and availability of nickel, zinc and lead in metal-contaminated calcareous loam soils. J. Environ. Eng. Landsc. Management 25, 289–296.

5. Cakmak I, Kutman UB. 2018. Agronomic biofortification of cereals with zinc: a review. European Journal of Soil Science 69, 172–180.

6. Chaudhary S, Singh H, Singh S, Singh V. 2014. Zinc requirement of green gram (*Vigna radiata*)–wheat (*Triticum aestivum*) crop sequence in alluvial soil. Indian Journal of Agronomy 59: 48-52.

7. Edward Raja M and Iyengar BRV. 1986.Chemical pools of zinc in some soils as influenced by sources of applied zinc. Journal of Indian Society of Soil Science 34:97-105.

8. Hakim S, Naqqash T, Nawaz MS, Laraib I, Siddique MJ, Mirza MS.2021.Rhizosphere engineering with plant growth promoting microorganisms for agriculture and ecological sustainability. Frontier Sustainability Food System:617157.

9. Hussain A, Arshad M, Zahir AZ and Asghar M.2019. Prospects of zinc solubilizing bacteria for enhancing growth of maize. Pak. J. Agric. Sci. 52, 915–922.

10. Hussain S, Ara T, Raina F, Gani G, Hussain N, Hussain M and Dar S. 2015. Quality evaluation of different forms of compost and their effect in comparison with inorganic fertilizers on growth and yield attributes of wheat (*Triticum aestivum* L.). Journal of Agricultural Science 7 (1): 154.

11. Imran A, Hakim S, Tariq M, Nawaz MS, Laraib I, Gulzar U., et al. 2021. Diazotrophs for lowering nitrogen pollution crises; looking deep into the roots. Front. Microbiol.:637815.

12. Imran M, Kanwal S, Hussain S, Aziz T and Maqsood MA. 2015. Efficacy of Zinc application methods for concentration and estimated bioavailability of Zinc in grains of rice growing on a calcareous soil. Pak. J. Agri. Sci. 52, 169–175.

13. Jackson, M.L. 1973. Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi, 498.

14. Kamran S, Shahid I, Baig DN, Rizwan M, Malik KA and Mehnaz S. 2017. Contribution of Zinc solubilizing bacteria in growth promotion and Zinc content of Wheat. Frontier Microbiology 8 :2593.

15. Kulhare PS, Sharma GD, Sharma BL, Khampariya RS. 2014. Direct and residual effect of Zn and organic manure on yield, Zn content and uptake in a rice-wheat sequence on a Vertisol. Indian Society of Soil Science 62(3): 274-279.

16. Lacerda JSM, Prieto HE, Pedrosa AW, Clemente JM, Santos RHS, Oliveria GL., et al. 2018. Importance of zinc for arabica coffee and its effects on the chemical composition of raw grain and beverage quality. Crop Sci. 58, 1360–1370.

17. Lindsay WL and Norvell WA. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Science Society of America journal 42(3):421-428.

18. Maillard AS, Diquelou V, Billard P, Laine M, Garnica M, Prudent, et al. 2015. Leaf mineral nutrient remobilization during leaf senescence and modulation by nutrient deficiency. Front. Plant Sci. 6:317.

19. Meena MC, Patel KP, and Rathod DD. 2006. Effect of Zn and Fe enriched FYM on mustard yield and micronutrient availability in loamy sand soil (*Typic Haplustept*) of Anand. Journal of the Indian Society of Soil Science,54(4): 495-499.

20. Meena Ramjas, Ajeet Kumar, Meena Sunita Kumari, Singh Sanjay Kumar, Mohit Bairwa 2024. Zinc Solubilizing Bacteria: A sustainable approach for enhancing agricultural productivity and soil health. New Era Agriculture Magazine, 3 (5), pp.90-95. ffhal-04768233f

21. Milkha M S and Garg A K.2010.Effectoflong-termfertilizer management and crop rotations on accumulation and down ward movement of phosphorus in semi-arid subtropical irrigated soils. Communications in soil science and plant analysis 41(7):848-864.

22. Mishra IG, Sapre S and Tiwari S. 2017. Zinc solubilizing bacteria from the rhizosphere of rice as prospective modulator of zinc bio-fortification in rice. Rhizosphere 3, 185–190.

23. Moharana PC, Biswas DR and Datta SC. 2015.Mineralization of nitrogen, phosphorus and sulphur in soil as influenced by rock phosphate enriched compost and chemical fertilizers. Journal of the Indian Society of Soil Science 63(3):283-293.

24. Olsen, S.R., Cole, C.V. and Watanabe, F.S. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No. 939, US Government Printing Office, Washington DC.

25. Prasad R, Prasad BL and Saka Rl. 1996. Effect of submergence on the transformation of zinc forms in old alluvial soils growing rice as related to soil properties. Transformation of applied soil zinc. J. Indian Soc. Soil Sci. 44: 74-76.

26. Rathod DD, Meena MC, Patel KP. 2012. Effect of different Zn-enriched organics on yields and micronutrient uptake under wheat-maize (Fodder) cropping sequence in semi-arid region of Gujarat. Indian Journal of Dryland Agricultural Research and Development27(1): 37-42.

27. Rehman R, Asif M, Cakmak I and Ozturk L. 2021. Differences in uptake and translocation of foliar applied Zn in maize and wheat. Plant Soil 462, 235–244.

28. Subbiah BV and Asija GL.1956. A rapid procedure for the estimation of available nitrogen in soils. Current Science25:259-260.

29. Suganya A, Saravanan A, Baskar M, Pandiyarajan P, Kavimani R. 2021. Agronomic biofortification of maize (*Zea mays L.)* with zinc by using of graded levels of zinc in combination with zinc solubilizing bacteria and Arbuscular mycorrhizal fungi. Journal of Plant Nutrition 44, 988 994.

30. Walkley A and Black IA. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37(1): 29-38.

31. Wijebandara DMDI, Dasog GS, Patil PL and Hebbar M. 2011. Zinc fractions and their relationships with soil properties in paddy-growing soils of northern dry and hill zones of Karnataka. Journal of the Indian Society of Soil Science 59(2): 141-147.

