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Combined Application of Zinc-Based Fertilizers and Biofertilizers Enhances Soil Fertility in Alkaline Soils of Uttar Pradesh, India

Rajesh Samota [a], Suresh Kumar [a*], Gayatri Pralhad Turkar [b], Shweta Gupta [c], Madhulika [d], Ankur Tripathi [e], Shubhendu Singh [d], Deepak Kumar Dwivedi [f], Basant Tamang [f], Gograj Ola [g], Surendra Kumar [h] and Umesh Kumar [i]

[a] Department of Soil Science and Agricultural Chemistry, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya (224229), Uttar Pradesh, India.
[b] Department of Soil Science and Agricultural Chemistry, JNKVV, Jabalpur, Madhya Pradesh, India.
[c] Teaching Associate, Department of Agronomy, CSAUA&T, Kanpur, India.
[d] Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India.
[e] SMS, Agronomy, KVK, Agra, Uttar Pradesh, India.
[f] SNRM, CPGS-AS, (Central Agricultural University-Imphal), Umiam, Shillong, Meghalaya, India.
[g] Department of Agronomy, SKRAU, Bikaner, Rajasthan, India.
[h] Dept of Vegetable Science, CoA-Imphal, (CAU-Imphal), Manipur, India.
[i] Department of SSAC, SVPUA&T, Modipuram, Meerut, Uttar Pradesh, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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**Corresponding author: E-mail: skumarpubs@gmail.com;*

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ABSTRACT

Soil fertility is a cornerstone of sustainable agricultural productivity, particularly in regions where edaphic constraints limit crop performance. The integrated use of zinc-based fertilizers and biofertilizers offers a promising approach to address the dual challenges of micronutrient deficiency and declining soil health in alkaline soils. The study aims to evaluate the effect of zinc-based fertilizers and zinc-mobilizing biofertilizer on soil fertility under silty loam soil conditions. The field experiment was conducted during the 2022 Kharif season at the Student Instructional Farm, Acharya Narendra Deva University of Agriculture and Technology, Ayodhya, Uttar Pradesh, India. The study involved eight treatments, including various combinations of recommended fertilizer dose (RDF), zinc sulphate, zinc oxide, and zinc-mobilizing bacteria (ZMB), arranged in a randomized block design with three replications. The results showed that the combined use of RDF with 5.0 kg ha^{-1} zinc sulphate and ZMB significantly enhanced soil fertility indices, including pH, organic carbon, and available macro- and micronutrients. The application of RDF (100%) + 5.0 Zn ha^{-1} (zinc sulphate) + biofertilizer (ZMB) recorded the highest nutrient availability (N, P, K) in the soil during post-harvest analysis.

Keywords: Zinc; soil bacteria; soil fertility; biofertilizer.

1. INTRODUCTION

Zinc (Zn) is imperative for both human development and crop production (Sultan *et al*., 2023). It is considered the most important micronutrient for normal and healthy plant growth. It is a structural component or cofactor of various enzymes involved in many biochemical processes (Saboor *et al*., 2021). Zn plays a crucial role in various physiological and biochemical processes in plants, including enzyme activation, protein synthesis, and membrane integrity. Deficiency of zinc is a major constraint in rice-growing areas, especially in calcareous, alkaline, and submerged soils where zinc becomes unavailable to plants. Studies have reported that nearly 50% of Indian soils are deficient in available zinc, severely limiting crop yields and grain nutritional quality (Cakmak, 2009; Sethi *et al.,* 2025). Soil fertility is a cornerstone of sustainable agricultural productivity, particularly in regions where edaphic constraints limit crop performance. In the Indo-Gangetic plains of Uttar Pradesh (U.P.), a significant proportion of agricultural land is characterised by alkaline soils, which pose a major challenge to nutrient availability and uptake. Alkaline soils, typically with a pH above 8.0, are known to impede the solubility and mobility of essential micronutrients notably zinc (Zn)-thereby affecting plant growth, yield, and nutritional quality. Zinc is a vital micronutrient involved in numerous physiological and biochemical processes in plants, including enzyme activation, protein synthesis, and growth regulation (Jagadeesh *et al.,* 2025). Its deficiency is widespread in Indian soils, particularly in alkaline and calcareous regions, where zinc becomes immobilised and unavailable to plants. According to recent estimates, over 50% of soils in U.P. are zinc-deficient, leading to suboptimal crop yields and reduced grain quality (Singh *et al.*, 2005). Conventional zinc fertilisation, such as the application of zinc sulphate ($ZnSO_4$), has been widely practised; however, its efficiency is often compromised by rapid fixation in high-pH soils. In this context, chelated forms of zinc, such as, have emerged as more effective alternatives due to their higher solubility and sustained release. Simultaneously, the use of biofertilizers-microbial inoculants that enhance nutrient availability through biological processes-has gained prominence as an eco-friendly and cost-effective strategy. Biofertilizers such as ZMB not only improve zinc availability but also contribute to better root development and microbial activity in the rhizosphere, potentially enhancing micronutrient uptake (Yadav *et al.,* 2020). The integrated use of zinc-based fertilisers and biofertilizers offers a promising approach to address the dual challenges of micronutrient deficiency and declining soil health in alkaline soils. While individual effects of zinc fertilisers and biofertilizers have been studied extensively, there is limited research on their synergistic impact under field conditions in the alkaline soils of U.P.

Traditional zinc fertilization methods, such as the application of zinc sulphate or zinc oxide, are often inefficient due to the rapid conversion of zinc into insoluble forms in high pH soils. Moreover, the excessive and unbalanced use of chemical fertilizers adversely affects soil health and sustainability. An eco-friendly alternative is the use of biofertilizers such as ZMB, which are known to solubilize unavailable zinc and enhance its uptake by plants. These bacteria not only improve zinc availability but also promote plant growth by secreting organic acids, phytohormones, and other growth-promoting substances. The integrated use of chemical zinc sources and ZMB has the potential to enhance soil fertility. However, studies on their combined effect under the specific agro-climatic conditions of eastern Uttar Pradesh, especially in silty loam soils, are limited.

Therefore, the present investigation was undertaken to study the effect of zinc-based fertilizers and zinc-mobilizing biofertilizer on soil fertility under silty loam soil conditions.

2. MATERIALS AND METHODS

Study Area: The field experiment was conducted during the *Kharif*, 2022, at the Student Instructional Farm, Acharya Narendra Deva University of Agriculture and Technology, Ayodhya, Uttar Pradesh, situated in the alkaline soil region of Uttar Pradesh, India. The experimental site is characterized by a semi-arid climate with average annual rainfall of approximately 700 mm.

Experimental Design: The study was laid out in a randomized block design (RBD) with three replications. The treatments consisted of combinations of zinc-based fertilizers and biofertilizers applied to rice. The following treatments were evaluated: Eight treatments were arranged in a Randomized Block Design (RBD) with three replications: T_1: RDF (150:60:40 kg N:P: K ha^{-1}), T_2: RDF + 2.5 kg Zn ha^{-1} (Zinc sulphate), T_3: RDF + 5.0 kg Zn ha^{-1} (Zinc sulphate), T_4: RDF + 2.5 kg Zn ha^{-1} (Zinc oxide), T_5: RDF + 5.0 kg Zn ha^{-1} (Zinc oxide), T_6: RDF + Biofertilizer (ZMB), T_7: RDF + 5.0 kg Zn ha^{-1} (Zinc sulphate) + Biofertilizer (ZMB), T_8: RDF + 2.5 kg Zn ha^{-1} (Zinc sulphate) + 2.5 kg Zn ha^{-1} (Zinc oxide) + Biofertilizer (ZMB).

Soil and Fertilizer Application: To nourish the rice, a fertilizer dose of 150:60:40 kg NPK ha^{-1} was applied. Half of the nitrogen dose and the full dose of phosphorus and potassium were administered as basal through urea, diammonium phosphate (DAP), and muriate of potash (MOP). The remaining nitrogen dose was applied in two equal portions during the tillering and panicle initiation stages of the crop. Zinc fertilizer was applied according to specific treatments, with the entire dose administered at the time of transplanting as a basal application.

Soil Analysis: Soil samples were collected at harvest to assess post-treatment changes in fertility status. Parameters analyzed included: Soil pH and EC (using pH meter and conductivity meter) Jackson, (1973); Organic carbon (Walkley and Black method) Walkley and Black, (1934); Available N (Alkaline $KMnO_4$ method) Subbiah and Asija, (1956); Available P (Olsen's method) Olsen (1954); Available K (Flame photometry) Hanway and Heidel, (1952); and Available Zn (DTPA extraction followed by AAS) Lindsay and Norvell, (1978). Initial soil analysis is shown in Table 1.

Statistical Analysis: Data were subjected to analysis of variance (ANOVA) using SPSS Statistics 21. Treatment means were compared using the least significant difference (LSD) test at a 5% level of significance ($p < 0.05$).

Table 1. Initial physico-chemical properties of experimental soil

Soil Properties	Value (Unit)
Mechanical analysis	
Sand	27.7 %
Silt	54.1 %
Clay	18.2 %
Textural class	Silty loam
Physico-chemical properties	
Bulk density (Mg m^{-3})	1.39 Mg kg^{-1}
pH	8.36
EC	0.34 dSm^{-1}
Organic Carbon	3.65 g kg^{-1}
Available N	170.1 kg ha^{-1}
Available P	13.1 kg ha^{-1}
Available K	270.8 kg ha^{-1}
Available Zn	0.51 ppm

3. RESULTS AND DISCUSSION

The data regarding the effect of zinc-based fertilizer and biofertilizers (ZMB) on soil pH is given in Table 2. There was no significant difference observed with the application of treatments. The highest value of pH (8.34) was observed with T_1: 100% RDF, and the lowest value (8.08) was observed with T7: RDF + 5.0 kg Zn ha^{-1}(Zinc sulphate) + ZMB. Electrical conductivity remained non-significant between the treatments, but there is a slight decrease from the initial level (0.34 dSm^{-1}) to harvest (0.24 dSm^{-1}). However, the lowest EC (0.24 dSm^{-1}) at harvest was recorded with T_7: RDF +5.0 kg Zn ha^{-1} (Zinc sulphate) + ZMB, and the highest EC (0.34 dSm^{-1}) was observed with T_1: 100% RDF. The highest organic carbon (4.20 g kg^{-1}) was observed with T_7: RDF +5.0 kg Zn ha^{-1} (Zinc sulphate) + ZMB, it was at par with T_8, T_6, T_3 and T_2 and the lower organic carbon (3.67g kg^{-1}) was observed with T_1: 100% RDF. Increased plant biomass produced by fertilizers results in increased returns of organic material to the soil in the form of decaying roots, litter, and crop residues. These results were also corroborated by the findings of Chandra et al. (2021) and Nath et al. (2019).

Table 2. Effect of zinc-based fertiliser and biofertilizer (ZMB) on soil pH, electrical conductivity, and organic carbon

Treatment	pH (1:2.5)	EC (dSm^{-1})	OC (g kg^{-1})
T_1: RDF 100% (150:60:40)	8.34	0.34	3.67
T_2: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate)	8.21	0.29	3.97
T_3: RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate)	8.17	0.27	4.02
T_4: RDF + 2.5 kg Zn ha^{-1} (Zinc Oxide)	8.30	0.32	3.88
T_5: RDF + 5.0 kg Zn ha^{-1} (Zinc Oxide)	8.23	0.31	3.90
T_6: RDF + Biofertilizer (ZMB)	8.16	0.26	4.06
T_7: RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate) + Biofertilizer (ZMB)	8.08	0.24	4.14
T_8: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate) + 2.5 kg Zn ha^{-1} (Zinc Oxide) + ZMB	8.10	0.25	4.20
SEm ±	0.06	0.02	0.09
C.D. (P = 0.05)	NS	NS	0.27

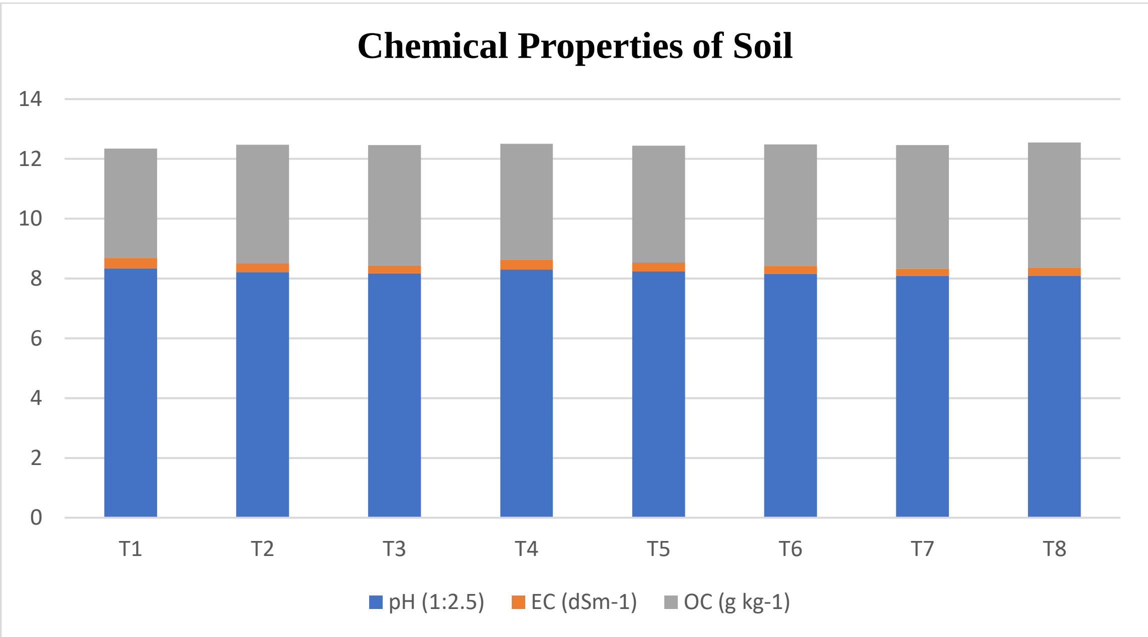

Fig. 1. Effect of ZMB on pH, Electrical Conductivity and Organic Carbon

Data regarding available nitrogen in soil after harvest of crop as affected by zinc-based fertilizer and ZMB is given in Table 3. Data clearly showed that available nitrogen was influenced significantly by different zinc-based fertilizers. Maximum value (182.87 kg ha^{-1}) was obtained with T_7: RDF +5.0 kg Zn ha^{-1} (Zinc sulphate) + ZMB, which was significantly at par with T_8 (181.90 kg ha^{-1}), T_6 (179.23 kg ha^{-1}) and T_3 (177.93 kg ha^{-1}). This might be due to solubilization of other forms of soil minerals and enhanced availability of nitrogen by the liquid biofertilizers. These findings are confirmed by Shahane *et al.* (2020). The maximum available phosphorus (15.10 kg ha^{-1}) was observed with T_7: RDF + 5.0 kg Zn ha^{-1} (Zinc sulphate) + ZMB. Treatment T_8 and T_6 were found to be at par with each other for the soil available P. These remaining five treatments were significantly superior to the other treatments. This might be due to the solubilization of the bound form of soil minerals and enhanced availability of nutrients in the soil for plant growth and development by the liquid biofertilizers. The findings of this investigation are confirmed by Nath *et al.* (2019) and Nataraja *et al*. (2021).

Potassium content among soils under various treatments containing organic inputs with zinc and liquid biofertilizer was found to be significantly higher than other treatments. The maximum available potassium was observed with the application of T_7: RDF +5.0 kg Zn ha^{-1} (Zinc sulphate) + ZMB, which was significantly at par with T_8 (279.53 kg ha^{-1}), T_6 (277.67 kg ha^{-1}) and T_3 (277.02 kg ha^{-1}) and minimum available potassium (271.33 kg ha^{-1}) was observed with T_1: 100% RDF followed by T_4. The reason for this may be attributed to higher available potassium by the agency of more number of active nutrients mobilizing bacteria assumed to be present under present under such treatments. This might be due to the solubilization of the bound form of soil minerals and enhanced availability of nutrients in the soil by the liquid biofertilizer. These findings are confirmed by Shahane *et al*. (2020).

Table 3. Effect of zinc-based fertiliser and biofertilizer (ZMB) on available nutrients (kg ha^{-1})

Treatment	N	P	K
T_1: RDF 100% (150:60:40)	174.37	13.33	271.33
T_2: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate)	177.17	14.03	275.15
T_3: RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate)	177.93	14.10	277.02
T_4: RDF + 2.5 kg Zn ha^{-1} (Zinc Oxide)	175.27	13.68	273.57
T_5: RDF + 5.0 kg Zn ha^{-1} (Zinc Oxide)	176.10	13.87	274.33
T_6: RDF + Biofertilizer (ZMB)	179.23	14.47	277.67
T_7: RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate) + Biofertilizer (ZMB)	182.87	15.10	282.40
T_8: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate) + 2.5 kg Zn ha^{-1} (Zinc Oxide) + ZMB	181.90	14.77	279.53
SEm ±	1.76	0.33	1.90
C.D. (P=0.05)	5.14	0.96	5.55

Table 4. Effect of zinc-based fertiliser and ZMB on available zinc in soil

Treatment	Zn (ppm)
T_1: RDF 100% (150:60:40)	0.54
T_2: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate)	0.57
T_3: RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate)	0.61
T_4: RDF + 2.5 kg Zn ha^{-1} (Zinc Oxide)	0.59
T_5: RDF + 5.0 kg Zn ha^{-1} (Zinc Oxide)	0.63
T_6: RDF + Biofertilizer (ZMB)	0.65
T_7: RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate) + Biofertilizer (ZMB)	0.67
T_8: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate) + 2.5 kg Zn ha^{-1} (Zinc Oxide) + ZMB	0.71
SEm ±	0.02
C.D. (P=0.05)	0.05

Data regarding available zinc in soil after harvest of crop as affected by zinc-based fertilizer in combination with other nutrient management practices during the study are given in Table 4. The data revealed that the application of T_8: RDF +2.5 kg Zn ha^{-1} (Zinc sulphate) + 2.5 kg Zn ha^{-1} (Zinc oxide) + ZMB, observed highest available zinc (0.71 ppm) content in soil which was significantly at par with T_7: RDF +5.0 kg Zn ha^{-1} (Zinc Sulphate) + ZMB. The minimum available zinc (0.54 ppm) was observed in soil with T_1: 100% RDF, followed by T_2: RDF + 2.5 kg Zn ha^{-1} (Zinc Sulphate). The data clearly indicated that the inoculation of zinc mobilizing bacteria affects on availability of Zn in soil. Zinc solubilizing bacteria, for example, *Bacillus sp*. produce organic acids, viz., gluconic acid. Gluconic acid is a major anion which helps in the solubilization of insoluble Zn compounds, resulting in increased availability of Zn. These results were also corroborated by the findings of Dinesh *et al*. (2018).

4. CONCLUSION

The application of RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate) + ZMB has non significantly effect on pH, Electrical Conductivity and also application of RDF + 5.0 kg Zn ha^{-1} (Zinc Sulphate) + ZMB has significantly influenced Organic carbon, Available N, P, K and Zn.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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