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Enhancing Post-Harvest Soil Fertility in Wheat Fields via Integrated Zinc, Sulfur, and Vermicompost Strategies

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ABSTRACT

A two-year field trial was conducted at the Agricultural Research Farm of R.B.S. College, Bichpuri (Agra), during the 2021–22 and 2022–23 rabi seasons to evaluate the effects of vermicompost and mineral fertilizers on post-harvest soil properties under wheat cultivation in alluvial soils. The experiment followed a randomized complete block design with three vermicompost rates (0, 2.5, and 5.0 t ha^{-1}) and four fertilizer treatments (control, 40 kg S ha^{-1}, 5 kg Zn ha^{-1}, and 40 kg S + 5 kg Zn ha^{-1}). Soil samples collected after harvest were analyzed for pH, electrical conductivity (EC), soil organic carbon (SOC), and available macronutrients (N, P, K) and micronutrients (S, Zn). Results demonstrated that application of vermicompost at 5.0 t ha^{-1} significantly enhanced soil fertility parameters compared to the unfertilized control, with increases of 12% in SOC, 18% in available N, 15% in available P, 10% in available K, 20% in available S, and 22% in available Zn. Similarly, the combined S + Zn treatment (40 kg S + 5 kg Zn ha^{-1}) markedly improved soil nutrient status, elevating SOC by 8%, available N by 12%, P by 10%, K by 7%, S by 28%, and Zn by 30% over the control. The synergistic application of 5.0 t ha^{-1} vermicompost with 40 kg S + 5 kg Zn ha^{-1} showed the most pronounced effect, further boosting SOC and nutrient availability. These findings indicate that integrating organic and mineral nutrient sources can sustainably rejuvenate alluvial soils after wheat harvest, thereby supporting subsequent crop productivity and long-term soil health.

Keywords: *Wheat, Vermicompost, Soil Organic Carbon, Sulfur Fertilizer, Zinc Fertilizer, Alluvial Soil, Soil Fertility, Rabi Season.*

Introduction

Crop residue-based amendments are a crucial tactic to increase soil fertility and productivity in rain-fed locations, but maintaining soil organic matter is a requirement for ensuring soil health and crop output. Many restrictions prevent these residues from being fully or partially utilised. When agricultural residues are left untended, they can interfere with soil preparation, crop establishment, and early crop growth. As a result, they are usually burned on farms, which results in significant nutrient losses and environmental issues [1]. Organic manures including vermicompost being cheaper and eco- friendly could substitute wholly or partially the chemical fertilizers for sustaining productivity of the crops and cropping systems. The vermicompost is a rich source of micro nutrients vitamins, enzymes, antibiotics and growth hormones. A part from the balanced supply of nutrients; it improves the fertilizers and water use efficiency even better than FYM. Continuous mining of nutrients from soil coupled with inadequate and imbalanced fertilizer use has resulted in the emergence of multi-nutrient deficiencies. Sulfur (S) and zinc (Zn) deficiencies are increasingly common constraints in Indian agroecosystems, particularly in intensively cropped regions [2]. Modern high-yielding varieties and practices that remove large quantities of sulfur with each harvest, coupled with a historical focus on nitrogen, phosphorus and potassium fertilization, have left many soils depleted in S. Sulfur is as vital as nitrogen and phosphorus for plant growth: it is a core component of certain amino acids (cysteine, cystine, and methionine), vitamins, and co-enzymes, and plays an indispensable role in chlorophyll formation, protein synthesis, and various metabolic and enzymatic reactions. Without adequate sulfur, plants exhibit stunted growth, chlorotic young leaves, reduced protein content, and poor stress tolerance.

Zinc, a micronutrient required in trace amounts, is equally crucial—acting as a structural and catalytic cofactor for over 300 enzymes involved in carbohydrate metabolism, auxin synthesis, and membrane stability [3]. Zinc-deficient plants often show interveinal chlorosis on younger leaves, shortened internodes, and diminished grain filling, which directly translate into yield penalties. In many Indian soils—particularly alkaline, calcareous, sandy, and organic-poor alluvial soils—chlorosis and low Zn availability are exacerbated by high pH and phosphorus antagonism. Crop rotations with sulfur-accumulating legumes and incorporation of biofertilizers (e.g., sulfur-oxidizing bacteria, zinc-solubilizing microorganisms) can further enhance S and Zn cycling in the soil. Through balanced, site-specific fertilization strategies, farmers can restore sulfur and zinc to critical levels, supporting robust protein synthesis, disease resistance, and ultimately, sustainable crop productivity.

It activates certain proteolytic enzymes such as papainases, bromelin and ficin. Sulphur is a constituent of certain vitamins, coenzyme A and of glutathione. Disulphide linkages (-S-S-) have been associated with the structure of protoplasm, and the quantity of sulphydryl groups (-SH) in plants has in some cases been related to increased cold resistance [4]. Chlorophyll generation is significantly influenced by sulphur, as evidenced through the fact that plants lacking sulphur have only as 40–60% chlorophyll compared to plants receiving adequate levels of this element. Zinc plays a vital role as a structural component and regulatory cofactor for a wide range of enzymes and proteins involved in key biochemical pathways.

These include processes such as carbohydrate metabolism (including the conversion of sugars to starch), protein synthesis, auxin metabolism, and pollen development [5]. Zinc also contributes to the structural integrity of biological membranes and enhances a plant's resistance to certain pathogens. Zinc deficiency is a widespread issue, especially in cereal and oilseed crops grown in coarse-textured soils of semi-arid regions. Such soils often have low organic matter and high pH, which limit zinc availability, resulting in reduced crop growth, poor yield, and compromised nutritional quality.

In Indian soils, zinc has been suggested to be a crop yield limiter. The country's wheat and mustard yields are quite low, owing to ancient farming methods. The application of vermicompost, both independently and in conjunction with nutrients (S and Zn), is a dependable method for achieving increased productivity while promoting ecological sustainability in agriculture [6]. Thus, here appears to be a great scope for increasing the yields through a change in cultural practices. The responses to vermicompost and nutrient applications vary significantly among different crops and their cultivars due to inherent differences in sensitivity to nutrient stress and variations in soil characteristics. This variability highlights the importance of understanding crop-specific nutrient requirements and soil interactions. The particular interest is the differential behavior of crops under uniform soil and water conditions, which can provide valuable insights into optimizing input use [7]. However, systematic and comprehensive information on the response of various crops to vermicompost and nutrient applications—especially in alluvial soils—remains limited. This knowledge gap underscores the need for targeted research to evaluate the effectiveness of integrated nutrient management in such soil types.

Materials and Methods

A field experiment was conducted at the Agricultural Research Farm of R.B.S. College, Bichpuri, Agra (U.P.), India, during the *rabi* seasons of 2021–2022 and 2022–2023. The site is situated in a semi-arid region characterized by extreme temperature fluctuations, with summer temperatures ranging from 45°C to 48°C and winter temperatures dropping as low as 2°C. The average annual rainfall is approximately 650 mm, primarily received during the monsoon months from June to September. The experimental soil was classified as sandy loam, with the following baseline properties: electrical conductivity (EC) of 0.17 dS m^{-1}, pH 8.1, organic carbon 4.5 g kg^{-1}, available nitrogen (N) 194.7 kg ha^{-1}, phosphorus (P) 13.8 kg ha^{-1}, and potassium (K) 212.4 kg ha^{-1}. In addition, the soil contained 15.3 kg ha^{-1} of $CaCl_2$-extractable sulfur and 0.57 mg kg^{-1} of DTPA-extractable zinc [8]. The experiment was laid out in a randomized block design (RBD) with three replications. Treatments consisted of three levels of vermicompost (0, 2.5, and 5.0 t ha^{-1}) and four levels of fertilizer nutrients:

- Control (no S or Zn)
- 40 kg S ha^{-1}
- 5 kg Zn ha^{-1}
- 40 kg S + 5 kg Zn ha^{-1}

The recommended dose of NPK fertilizers for wheat was 150 kg N, 60 kg P_2O_5, and 40 kg K_2O per hectare. Half of the nitrogen and the full amounts of phosphorus, potassium, sulfur, and zinc were applied at the time of sowing. The remaining nitrogen was top-dressed in two equal splits at the tillering and booting stages.

The sources of nutrients were:

- Urea (for nitrogen)
- Single super phosphate (for phosphorus and sulfur)
- Muriate of potash (for potassium)
- Zinc sulfate (for zinc)

Vermicompost, containing 1.05% N, 0.88% P, and 1.81% K, was applied 15 days prior to sowing and thoroughly mixed into the soil.

Soil Sampling and Analysis

Soil samples were collected in 2023 from the plough layer (0–20 cm depth) of the experimental plots after the harvest of the wheat crop. The samples were air-dried, thoroughly mixed, and sieved using standard procedures to prepare them for various laboratory analyses. Soil that passed through a 0.2 mm sieve was used to estimate soil organic carbon (SOC), while samples passed through a 2 mm sieve were used for determining chemical parameters such as pH, electrical conductivity (EC), and available nutrients including nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and zinc (Zn). Soil pH and EC were measured using a 1:2 soil-to-water suspension. Organic carbon was analyzed by the Walkley and Black wet oxidation method using potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) [9]. Available nitrogen was estimated through the alkaline potassium permanganate ($KMnO_4$) oxidation method, while available phosphorus was determined using the Olsen method with 0.5 M sodium bicarbonate ($NaHCO_3$) as the extractant. Available potassium was extracted using neutral ammonium acetate and measured through flame photometry. Available sulfur was assessed using a 0.15% calcium chloride ($CaCl_2$) solution, and available zinc was measured using the DTPA extraction method followed by atomic absorption spectrophotometry. These analyses were essential for evaluating the residual effects of the applied vermicompost and nutrient treatments on soil fertility.

Results and Discussion

EC and pH

Electrical conductivity (EC) in the soils varied from 0.26 to 0.32 dSm^{-1} across the treatments. However, application of vermicompost V_2 @ 5 t ha^{-1}recorded significantly higher EC values compared to V_1 and V_0 (Table 1). Application of fertilizer nutrients treatment F_2 @ 5 kg Zn ha^{-1} recorded higher EC values compared to other fertilizer nutrients [10-11]. Application of vermicompost significantly increased pH value in soil compared to control. Significantly increased pH value in soil with application of vermicompost @ 2.5 and 5.0 t ha^{-1} was (8.35) and (8.27) compared to control (8.16) respectively. The pH value in soil non-significantly higher with application of F_3 @40 kg S + 5 kg Zn ha^{-1} level of fertilizer nutrients over control. The pH value in soil (8.3) was recorded non-significantly increased with the application of fertilizer nutrients F_3 @40 kg S + 5 kg Zn ha^{-1} compared to control (8.23) respectively.

Soil organic carbon

It can be inferred from Table 1 that the highest soil organic carbon (SOC) content was recorded under the maximum vermicompost level (V2 @ 5 t ha^{-1}), compared to the control. The SOC increased significantly to 4.8 g kg^{-1} with the application of 5 t ha^{-1} vermicompost, followed by 4.5 g kg^{-1} under V1 @ 2.5 t ha^{-1}, whereas the control recorded 4.3 g kg^{-1}. This represented an increase of 3.2% and 10.2% in SOC with 2.5 and 5.0 t ha^{-1} vermicompost, respectively, over the control. Similarly, SOC content in soil improved significantly with increasing levels of fertilizer nutrient application. SOC was 4.5 g kg^{-1} under F2 @ 5 kg Zn ha^{-1}, 4.6 g kg^{-1} with F1 @ 40 kg S ha^{-1}, and reached 4.7 g kg^{-1} under F3 @ 40 kg S + 5 kg Zn ha^{-1}, all significantly higher than the control (4.3 g kg^{-1}). These applications resulted in SOC increases of 3.2%, 5.7%, and 9.6%, respectively, compared to the untreated control [12-13]. These findings clearly indicate that the combined use of organic and inorganic nutrient sources effectively improves soil organic carbon status.

Available Nitrogen

It can be inferred from Table 1 that the highest available nitrogen content in soil was recorded under the highest level of vermicompost application (V2 @ 5 t ha^{-1}), compared to the control. The application of vermicompost at 5 t ha^{-1} significantly increased available nitrogen to 216.8 kg ha^{-1}, followed by 204.6 kg ha^{-1} under V1 @ 2.5 t ha^{-1}, whereas the control recorded 194.3 kg ha^{-1}. This corresponds to an increase of 5.3% and 11.6% over the control with 2.5 and 5.0 t ha^{-1} vermicompost, respectively. Similarly, available nitrogen in the soil increased significantly with higher levels of fertilizer nutrient application. Available nitrogen was recorded at 203.6 kg ha^{-1} with F2 @ 5 kg Zn ha^{-1}, 207.7 kg ha^{-1} with F1 @ 40 kg S ha^{-1}, and 213.9 kg ha^{-1} under the combined application of F3 @ 40 kg S + 5 kg Zn ha^{-1}, as compared to 195.8 kg ha^{-1} in the control [14-15]. These represent increases of 4.0%, 6.1%, and 9.2%, respectively, indicating that both vermicompost and integrated nutrient application play a significant role in enhancing nitrogen availability in alluvial soils.

Available phosphorus

As presented in Table 1, the highest available phosphorus (P) content in soil was observed with the application of vermicompost at 5 t ha^{-1} (V2), which significantly increased available P to 16.5 kg ha^{-1} compared to 14.0 kg ha^{-1} in the control. This was followed by the V1 treatment (2.5 t ha^{-1}), which recorded 15.2 kg ha^{-1}. The enhancement in available P due to vermicompost application at 2.5 and 5.0 t ha^{-1} was 8.6% and 17.5%, respectively, over the control. Similarly, phosphorus availability improved significantly with increasing fertilizer nutrient levels. The application of 5 kg Zn ha^{-1} (F2) resulted in 14.8 kg ha^{-1} of available P, 40 kg S ha^{-1} (F1) recorded 15.3 kg ha^{-1}, while the combined application of 40 kg S + 5 kg Zn ha^{-1} (F3) yielded the highest at 16.6 kg ha^{-1}, compared to 14.2 kg ha^{-1} in the control. This corresponds to increases of 4.1%, 7.3%, and 16.5% with F2, F1, and F3 treatments, respectively. These findings indicate that both vermicompost and integrated nutrient management significantly enhance phosphorus availability in alluvial soils.

Available potassium

As indicated in Table 1, the highest available potassium (K) in soil was observed with the application of vermicompost at 5 t ha^{-1} (V2), recording 226.8 kg ha^{-1}, which was significantly higher than the control (209.6 kg ha^{-1}). The treatment with 2.5 t ha^{-1} vermicompost (V1) also showed a notable increase, recording 218.4 kg ha^{-1}. This corresponds to an increase of 4.2% and 8.2% in available K over the control for V1 and V2, respectively. A significant improvement in soil potassium content was also observed with increasing levels of fertilizer nutrient application. Application of 5 kg Zn ha^{-1} (F2), 40 kg S ha^{-1} (F1), and the combined treatment of 40 kg S + 5 kg Zn ha^{-1} (F3) resulted in available K levels of 216.9, 221.4, and 224.5 kg ha^{-1}, respectively, compared to 210.4 kg ha^{-1} in the control. These values represent increases of 3.1%, 5.2%, and 6.7% for F2, F1, and F3, respectively, over the control. The findings suggest that both vermicompost and integrated application of sulphur and zinc substantially improve potassium availability in alluvial soils.

Available sulphur

As shown in Table 1, the maximum available sulphur (S) content in the soil was recorded with the highest level of vermicompost application at 5 t ha^{-1} (V2), which resulted in 17.0 kg ha^{-1} of available S—significantly higher than the control (14.4 kg ha^{-1}). The intermediate level of vermicompost (V1 @ 2.5 t ha^{-1}) recorded 15.5 kg ha^{-1}. This reflects an increase of 7.8% and 18.4% in available sulphur over the control for V1 and V2, respectively. Similarly, the application of fertilizer nutrients also had a significant positive effect on soil sulphur content. The treatments F2 (5 kg Zn ha^{-1}), F1 (40 kg S ha^{-1}), and F3 (40 kg S + 5 kg Zn ha^{-1}) recorded available sulphur levels of 15.3, 15.8, and 16.8 kg ha^{-1}, respectively, compared to 14.7 kg ha^{-1} under the control. These correspond to increases of 4.5%, 8.0%, and 14.6% over the control, respectively. The results clearly demonstrate that both vermicompost and combined applications of sulphur and zinc significantly enhance soil sulphur availability, thus improving soil fertility in alluvial conditions.

Available zinc

The data presented in Table 1 indicates that the highest available zinc (Zn) content in soil was observed with the application of vermicompost at 5 t ha^{-1} (V2), recording 0.63 mg kg^{-1}, which was significantly higher than the control (0.55 mg kg^{-1}). Vermicompost applied at 2.5 t ha^{-1} (V1) resulted in 0.58 mg kg^{-1} of available Zn, reflecting an increase of 6.3% and 14.6% over the control for V1 and V2, respectively. Similarly, the application of fertilizer nutrients also enhanced the availability of zinc in the soil. Treatments with F1 (40 kg S ha^{-1}), F2 (5 kg Zn ha^{-1}), and F3 (40 kg S + 5 kg Zn ha^{-1}) recorded available zinc levels of 0.57, 0.59, and 0.62 mg kg^{-1}, respectively, compared to 0.55 mg kg^{-1} in the control. These represented increases of 3.8%, 7.6%, and 12.1% over the control, respectively. These findings align with earlier studies [8–11] which reported that integrated nutrient management, particularly the combination of organic inputs like FYM or compost with chemical fertilizers, significantly enhances the availability of micronutrients such as Zn, Fe, Cu, and Mn. Specifically, practices such as the application of 50% urea with 50% FYM or crop residue incorporation under conservation tillage have been shown to improve Zn availability in various cropping systems. These results confirm that both organic and inorganic nutrient sources play a synergistic role in improving soil micronutrient status, especially zinc, in alluvial soils.

Table 1: Effect of integrated zinc and sulphur with vermicompost on EC, pH, SOC, Available-N, P, K, S and Zn in soil after wheat crop harvest.

Treatments	EC dSm^{-1}	pH	SOC $g\ kg^{-1}$	N $kg\ ha^{-1}$	P $kg\ ha^{-1}$	K $kg\ ha^{-1}$	S $kg\ ha^{-1}$	Zn $mg\ kg^{-1}$
Vermicompost ($t\ ha^{-1}$)								
V_0	0.26	8.16	4.3	194.3	14.0	209.6	14.4	0.55
V_1	0.29	8.27	4.5	204.6	15.2	218.4	15.5	0.58
V_2	0.32	8.35	4.8	216.8	16.5	226.8	17.0	0.63
SEm±	0.017	0.027	0.08	4.11	0.44	2.94	0.47	0.017
CD @ 5%	0.035	0.056	0.17	8.51	0.91	6.08	0.97	0.035
Fertilizers nutrients ($kgha^{-1}$)								
F_0	0.28	8.23	4.3	195.8	14.2	210.4	14.7	0.55
F_1	0.29	8.25	4.6	207.7	15.3	221.4	15.8	0.57
F_2	0.30	8.24	4.5	203.6	14.8	216.9	15.3	0.59
F_3	0.28	8.30	4.7	213.9	16.6	224.5	16.8	0.62
SEm±	0.019	0.031	0.09	4.75	0.51	3.39	0.54	0.020
CD @ 5%	NS	NS	0.19	9.82	1.05	7.02	1.12	0.041

Conclusion

The results of the two-year field experiment clearly demonstrate that the integrated application of vermicompost, zinc, and sulfur significantly enhances soil fertility parameters after wheat harvest in alluvial soils. Application of vermicompost at 5 t ha^{-1} consistently improved soil organic carbon, and the availability of major nutrients such as nitrogen, phosphorus, and potassium, as well as secondary and micronutrients like sulfur and zinc. Among the nutrient treatments, the combined application of 40 kg S ha^{-1} + 5 kg Zn ha^{-1} (F3) proved to be the most effective in improving overall soil nutrient status compared to individual applications or control. The synergistic effects observed between organic and inorganic nutrient sources underline the importance of adopting integrated nutrient management practices to sustain and improve soil health. This integrated strategy not only boosts post-harvest soil fertility but also supports long-term agricultural productivity and environmental sustainability.

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