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Nishchay Kumar
M.Sc. Scholar, Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh, India

Ram Bharose
Professor, Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh, India

Arun A David
Professor, Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh, India

Shreshthi Maurya
Ph.D. Research Scholar, Sam Higginbottom University of Agriculture Technology and Sciences, Uttar Pradesh, India

Corresponding Author:
Nishchay Kumar
M.Sc. Scholar, Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh, India

Effect of application of NPK Zn and vermicompost in mustard cultivation on soil properties

Nishchay Kumar, Ram Bharose, Arun A David and Shreshthi Maurya

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Abstract
The present investigation was carried out on combined effects of varying levels of NPK, zinc, and vermicompost on soil health, crop growth, and yield performance of the mustard variety Varuna T-59. Conducted during the *Rabi* seasons of 2024-25 at the Research Farm of the Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh, India. The experiment was laid down in randomized block design (RBD) with twelve treatments *viz.*, T_1 (RDF NPK Zn @ 0%+ V.C. @ 0%); T_2 (RDF NPK Zn @ 0%+ V.C. @ 35%); T_3 (RDF NPK Zn @ 0%+ V.C. @ 70%); T_4 (RDF NPK Zn @ 0%+ V.C. @ 105%); T_5 (RDF NPK Zn @ 50%+ V.C. @ 0%); T_6 (RDF NPK Zn @ 50%+ V.C. @ 35%); T_7 (RDF NPK Zn @ 50%+ V.C. @ 70%); T_8 (RDF NPK Zn @ 50%+ V.C. @ 105%); T_9 (RDF NPK Zn @ 100%+ V.C. @ 0%); T_{10} (RDF NPK Zn @ 100%+ V.C. @ 35%); T_{11} (RDF NPK Zn @ 100%+ V.C. @ 70%) and T_{12} (RDF NPK Zn @ 100%+ V.C. @ 105%) to evaluate their impact on soil physico-chemical properties and crop performance. The integrated application of 100% RDF NPK and Zn at 100% with 70% vermicompost notably enhanced soil structure, as evidenced by reduced bulk and particle densities, and improved pore space and water holding capacity, thereby promoting better soil fertility. Among the treatments, T_{11} (RDF NPK Zn @ 100% + Vermicompost @ 70%) was superior, achieving the highest organic carbon (0.60%), soil pH (7.53), EC (0.43 dS/m), available nitrogen (277.51 kg/ha), phosphorus (34.70 kg/ha), potassium (196.60 kg/ha) and zinc (3.06 ppm/ha) at 0-15 cm.

Keywords: Organic carbon content, EC bulk density, *Brassica nigra*

Introduction
Soil health serves as the cornerstone of agricultural productivity and the long-term sustainability of ecosystems. However, the continuous depletion of essential nutrients, widespread soil erosion, and diminishing biodiversity pose significant challenges to farmers across the globe. In this context, vermicomposting has gained recognition as a promising approach to revitalize soil fertility and boost crop productivity (Chetankumar *et al.*, 2020) [3]. Mustard, commonly known as rai, is the most significant species among cruciferous oilseeds, occupying nearly 70% of the total area under rapeseed-mustard cultivation. India ranks as the world's largest producer of rapeseed-mustard, contributing 27.5% of the global cultivated area and 20% of total production (Vanukuri and Pandey 2022) [29]. Despite this prominence, the average yield in India has stagnated around 900 kg/ha, considerably lower than the global average of 1408 kg/ha (Patel, 2024) [17]. To mitigate these detrimental effects, recent agricultural practices are increasingly incorporating organic and biologically derived fertilizers. Among these, vermicompost-based bio-fertilizers have gained significant attention due to their sustainable and eco-friendly properties. Vermicompost, produced through the breakdown of organic matter by earthworms and associated microorganisms, is rich in essential plant nutrients, beneficial microbes, and growth-promoting substances, offering a viable alternative to synthetic fertilizers (Hong *et al.*, 2007) [8]. Unlike chemical inputs, vermicompost is biodegradable, non-toxic, and environmentally benign, posing no harm to humans, animals, or birds (Begum *et al.*, 2018) [1]. Thus, the adoption of vermicompost as a natural bio-fertilizer represents a promising step toward sustainable agriculture, fostering soil health, enhancing crop productivity, and reducing reliance on harmful agrochemicals. In light of the growing emphasis on sustainable agriculture, organic inputs like vermicompost have gained significant attention as viable alternatives to

chemical fertilizers. Zinc contributes significantly to both qualitative and quantitative crop production, influencing yield and overall plant performance (Suganya *et al.*, 2020) [27]. The application of Zn fertilizers has been reported to enhance grain yield, particularly when integrated with other essential nutrients. For instance, Mandal and Sinha (2004) [13] observed that supplementing NPK fertilizers with zinc (Zn) and boron (B) in mustard cultivation resulted in increased plant height, more branches per plant, a higher number of siliquae per plant, and an increased number of seeds per siliqua. Zinc deficiency in plants typically leads to stunted growth and reduced productivity (Chowhan and Islam, 2021) [4]. Plant zinc efficiency encompasses the ability to uptake, transport, and utilize Zn effectively. Nitrogen is a crucial macronutrient for wheat production, and improper application can significantly reduce yields, as it is essential for rapid plant growth and higher productivity per hectare. It is a key component of plant metabolism and a major constituent of living tissues. Deficiency of nitrogen hampers biomass accumulation and limits the efficient utilization of solar energy, thereby adversely affecting grain yield and yield attributes. Variability in soil properties and climatic conditions across farms influences nitrogen dynamics in the root zone, often leading to fluctuations in its availability and plant uptake (Espindula *et al.*, 2010) [5]. Phosphorus is another vital nutrient, directly associated with energy utilization and storage in plants, including processes like photosynthesis. It also supports normal growth and development, with commercial fertilizers deriving phosphorus from phosphate rock. Potassium, the third primary nutrient, enhances disease resistance, improves yield and quality, and provides tolerance against adverse conditions such as cold and drought by strengthening root systems and preventing wilting (Singh *et al.*, 2023) [23]. In modern agriculture, nitrogenous fertilizers are indispensable, yet only 20-50% of soil-applied nitrogen is recovered by annual crops, with the rest lost through denitrification, volatilization, and leaching. Such inefficiency not only lowers yields but also raises production costs, necessitating strategies to reduce losses and improve nitrogen-use efficiency. Conventional soil application of urea is often less effective compared to combined soil and foliar feeding. Foliar application of water-soluble fertilizers can enhance tillering, branching, flowering, yield, and maturity while reducing cultivation costs. This approach is particularly beneficial at critical growth stages when nutrient demand exceeds root uptake capacity (Fageria *et al.*, 2009) [6]. Furthermore, foliar feeding ensures better nutrient translocation from leaves to developing grains, thereby improving efficiency compared to sole soil application.

Materials and Methods

The present investigation was carried out at the Research Farm of Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh, during the *Rabi* seasons of 2024-25. The experiment was laid out in Randomized Block Design (RBD) with three levels of NPK, Zn and four levels of vermicompost. The treatments have been replicated three times. The different treatments were employed randomly in each replication. The treatments comprised of T_1 (RDF NPK Zn @ 0% + V.C @ 0%); T_2 (RDF NPK Zn @ 0% + V.C @ 35%); T_3 (RDF NPK Zn @ 0% + V.C @ 70%); T_4 (RDF NPK Zn @ 0% + V.C @ 105%); T_5 (RDF NPK Zn @ 50% + V.C @ 0%); T_6 (RDF NPK Zn @ 50% + V.C @ 35%); T_7 (RDF NPK Zn @ 50% + V.C @ 70%); T_8 (RDF NPK Zn @ 50% + V.C @ 105%); T_9 (RDF NPK Zn @ 100% + V.C @ 0%); T_{10} (RDF NPK Zn @ 100% + V.C @ 35%); T_{11} (RDF NPK Zn @ 100% + V.C @ 70%) and T_{12} (RDF NPK Zn @ 100% + V.C @ 105%). Soil samples from each experimental plot were collected at two depths (0-15 cm and 15-30 cm) following crop harvest. The samples were air-dried, finely ground, and sieved through a 2 mm mesh, after which they were stored in polythene bags for subsequent analysis. The processed samples were examined for a range of physico-chemical properties, including bulk density, particle density, pore space percentage (100 ml measuring cylinder method by Muthuvel *et al.*, 1992) [14], pH (Digital pH meter by Jackson, 1958) [9], electrical conductivity (Digital EC meter by Wilcox, 1950) [31], organic carbon (Wet method by Walkley and Black' 1934) [30], and available macronutrients like Nitrogen (Alkaline permanganate method by Subbiah & Asija 1956) [26], Phosphorus (Calorimetric method by Olsen *et al.*, 1954) [15], Potassium (Flame photometric method by Toth and Prince, 1949) [28] as well as zinc content (Spectrophotometer by Shaw and Dean 1952) [21]. The post-harvest soil characteristics, along with the analytical methods employed, are presented in Table 1. Analysis of Variance was worked out using Fisher and Yates (1963) [7].

Results and Discussion

Soil Physical parameters

Bulk density and particle density

The results of soil bulk density (table 2) at both 0-15 and 15-30 cm depths after crop harvest indicated non-significant differences among the treatments comprising varying levels of NPK, zinc, and vermicompost application. Although statistically non-significant, the maximum bulk density values of 1.29 and 1.32 Mg m^{-3} at 0-15 and 15-30 cm depths, respectively, were recorded under T_1 (RDF NPK Zn @ 0% + V.C. @ 0%). In contrast, the minimum bulk density values of 1.24 and 1.25 Mg m^{-3} at corresponding depths were observed in T_{11} (RDF NPK Zn @ 100% + V.C. @ 70%). The slight variation in bulk density across treatments, though not significant, may be attributed to differences in organic matter addition and soil structural modification induced by vermicompost and inorganic fertilizer levels. Since bulk density is inversely related to organic matter content and is influenced by compaction, texture, and porosity, the higher bulk density recorded in T_1 reflects the absence of external inputs. Similarly, particle density also showed non-significant variation across treatments. The highest particle density values of 2.59 and 2.61 Mg m^{-3} at 0-15 cm and 15-30 cm depths, respectively, were noted in T_1 (RDF NPK Zn @ 0% + V.C. @ 0%), while the lowest values of 2.50 Mg m^{-3} at both soil depths were observed in T_3 (RDF NPK Zn @ 0% + V.C. @ 70%). The observed non-significant variation in bulk density and particle density across treatments can be explained by the role of organic matter and soil mineral composition in governing soil physical properties. Bulk density is largely controlled by organic matter content, porosity, and soil compaction, whereas particle density depends primarily on the relative proportion of heavier mineral constituents such as quartz and feldspar in contrast to lighter organic matter. In T_1 (RDF NPK Zn @ 0% + V.C. @ 0%), where no external organic or inorganic inputs were applied, the highest bulk density (1.29 and 1.32 Mg m^{-3} at 0-15 and 15-30 cm, respectively) and particle density (2.59 and 2.61 Mg m^{-3}) were recorded. This may be attributed to the predominance of mineral particles with negligible dilution by organic matter, resulting in compact soil with higher density values. On the other hand, treatments receiving vermicompost (e.g., T_3 and T_{11}) exhibited relatively lower bulk and particle densities. The incorporation of vermicompost improves soil structure by increasing aggregation, enhancing pore space, and introducing lighter organic materials that reduce overall soil mass per unit volume. In T_{11} (RDF NPK Zn @ 100% + V.C. @ 70%), the lowest bulk density (1.24 and 1.25 Mg m^{-3}) was observed, while the lowest particle density (2.50 Mg m^{-3} at both depths) was noted in T_3 (RDF NPK Zn @ 0% + V.C. @ 70%). The reduction in density values under these treatments can be ascribed to the substantial addition of organic matter, which diluted the mineral fraction and improved porosity. Thus, even though the differences were statistically non-significant, the trend clearly suggests that increasing levels of vermicompost, particularly when applied in combination with recommended mineral fertilizers, tend to lower soil density values by modifying soil physical properties. These findings are in line with earlier reports (e.g., Sahu *et al.*, 2020) [18], which demonstrated the beneficial role of organic amendments in improving soil structure and reducing bulk and particle density.

Pore space

The assessment of percent pore space (table 2) at 0-15 and 15-30 cm soil depths after crop harvest revealed significant differences among the treatments involving varying levels of NPK, zinc, and vermicompost. The maximum pore space values were recorded in T_{11} (RDF NPK Zn @ 100% + V.C. @ 70%), with 50.21% at 0-15 cm and 48.16% at 15-30 cm depths, followed by T_{10} (RDF NPK Zn @ 100% + V.C. @ 35%), which showed 48.44% and 46.39% at the respective depths. In contrast, the lowest pore space values of 41.25% and 39.47% were observed under T_0 (RDF NPK Zn @ 0% + V.C. @ 0%). The significant variation in pore space can be attributed to the combined effects of organic and inorganic nutrient inputs on soil porosity and structural development. Percent pore space is closely linked with bulk density, organic matter content, and aggregation, all of which are influenced by fertilization practices. The superior pore space in T_{11} may be ascribed to the high dose of vermicompost supplemented with balanced NPK and zinc, which enhanced soil aggregation, increased organic carbon content, and stimulated microbial activity—factors that collectively promote stable aggregate formation and increased void space. Likewise, T_{10}, which received a moderate level of vermicompost (35%) along with full NPK and zinc, also exhibited relatively higher pore space, reflecting a dose-dependent improvement due to organic amendments. Conversely, T_0, which did not receive either organic or inorganic inputs, recorded the lowest pore space, likely due to compaction, poor aggregation, and reduced biological activity, leading to higher bulk density and reduced porosity. Similar conclusions regarding the beneficial role of zinc and vermicompost in enhancing soil porosity have also been reported by Singh *et al.* (2017) [25] and Sharma *et al.* (2017) [20].

Soil pH, EC and Organic carbon

The soil pH values (table 3) recorded at 0-15 and 15-30 cm depths after crop harvest revealed non-significant differences among treatments involving different levels of NPK, zinc, and vermicompost. Despite the lack of statistical significance, the maximum pH values (7.53 and 7.67) were observed in T_{11} (RDF NPK Zn @ 100% + V.C. @ 70%) and were at par with T_{12} (RDF NPK Zn @ 100% + V.C. @ 105%), which also recorded pH values of 7.53 and 7.67 at the corresponding depths. The minimum pH values (7.16 and 7.30) were noted in T_1 (RDF NPK Zn @ 0% + V.C. @ 0%). Similarly, soil electrical conductivity (EC) at both depths showed non-significant variation across treatments. The highest EC values (0.43 and 0.45 dS m^{-1}) were obtained in T_{11}, closely followed by T_{12} (0.42 and 0.43 dS m^{-1}). In contrast, the lowest EC values (0.34 and 0.37 dS m^{-1}) were recorded in T_5 (RDF NPK Zn @ 50% + V.C. @ 0%). In contrast to pH and EC, soil organic carbon content exhibited significant variation among treatments. The maximum organic carbon values of 0.60% and 0.58% were observed in T_{12} at 0-15 and 15-30 cm depths, respectively, followed by T_{11} (0.58% and 0.56%). The minimum organic carbon content (0.39% and 0.33%) was recorded in T_0 (RDF NPK Zn @ 0% + V.C. @ 0%). The soil pH and electrical conductivity (EC) measured at 0-15 and 15-30 cm depths after harvest showed non-significant differences among treatments with varying levels of NPK, zinc, and vermicompost. The highest pH values (7.53 and 7.67) were observed in T_{11} (RDF NPK Zn @ 100% + V.C. @ 70%) and T_{12} (RDF NPK Zn @ 100% + V.C. @ 105%), while the lowest values (7.16 and 7.30) occurred in T_1. Similarly, EC was highest in T_{11} (0.43 and 0.45 dS m^{-1}) and lowest in T_5 (0.34 and 0.37 dS m^{-1}). The lack of significance in pH and EC suggests that nutrient and organic amendments had minimal impact on soil reaction and soluble salt concentration, possibly due to the soil's buffering capacity. In contrast, organic carbon content varied significantly across treatments. The highest values were observed in T_{12} (0.60% and 0.58%), followed by T_{11} (0.58% and 0.56%), while the lowest were recorded in T_0 (0.39% and 0.33%). The significant improvement in organic carbon with vermicompost application is attributable to the direct addition of organic residues, enhanced microbial activity, and improved aggregation. These findings highlight the role of organic amendments in enriching soil carbon pools, even when pH and EC remain unaffected. Lautt *et al.* (2020) [12] and Saxena *et al.* (2017) [19] reported that soil parameter such as electrical conductivity (EC) accounted for only 12.62% of the variability, organic carbon.

Soil chemical parameters

Available nutrients

The post-harvest analysis of soil available nutrients (table 4) at 0-15 and 15-30 cm depths revealed significant variations among treatments receiving different levels of NPK, zinc, and vermicompost. For available nitrogen, the maximum values were recorded in T_{12} (RDF NPK Zn @ 100% + V.C. @ 105%), with 277.51 and 263.80 kg ha^{-1} at 0-15 cm and 15-30 cm depths, respectively, followed by T_{11} (272.30 and 258.59 kg ha^{-1}). The minimum values (201.78 and 181.78 kg ha^{-1}) were noted in T_0. Available phosphorus also showed significant differences, with T_{12} registering the highest values (34.70 and 26.71 kg ha^{-1}), succeeded by T_{11} (31.99 and 23.99 kg ha^{-1}). The lowest phosphorus levels (17.24 and 9.24 kg ha^{-1}) occurred in T_0. Similarly, available potassium content was highest in T_{12} (196.60 and 181.60 kg ha^{-1}) and next in T_{11} (194.44 and 179.44 kg ha^{-1}), while T_0 recorded the lowest values (178.10 and 160.34 kg ha^{-1}). Available zinc content followed the same trend, with T_{12} recording the highest concentrations (3.26 and 2.89 ppm) followed by T_{11} (3.06 and 2.72 ppm). The lowest zinc levels (1.82 and 1.46 ppm) were observed in T_0. The significant variation observed in the availability of N, P, K, and Zn among treatments can be attributed to the combined effects of mineral fertilizers and vermicompost on nutrient dynamics in the soil. The consistently higher nutrient levels in T_{12} (RDF NPK Zn @ 100% + V.C. @ 105%) and T_{11} (RDF NPK Zn @ 100% + V.C. @ 70%) reflect the synergistic role of organic and inorganic sources. Vermicompost provides readily mineralizable organic matter, enhancing microbial activity and enzymatic processes that accelerate nutrient mineralization and improve soil structure. This leads to better aeration, moisture retention, and enhanced cation exchange capacity, which collectively increase nutrient availability. Nitrogen availability was enhanced due to the gradual mineralization of organic N from vermicompost, supplementing the inorganic N supplied through fertilizers. Higher phosphorus availability in integrated treatments can be explained by the ability of organic acids released during decomposition to solubilize fixed P, while microbial activity also facilitates P mobilization. Similarly, potassium availability improved due to the release of K from vermicompost and reduced fixation through enhanced soil aggregation. Increased zinc availability in T_{12} and T_{11} may be attributed to the chelating action of organic matter, which prevents Zn precipitation and enhances its solubility. These results emphasize that integrated nutrient management not only improves nutrient availability but also sustains soil fertility by enriching the organic pool and enhancing microbial processes. Saxena *et al.* (2017) [19] reported same findings in soil zinc content on application of NPK and Zinc. Singh *et al.* (2018) [24] reported same findings in soil nitrogen and phosphorus content on application of NPK and Zinc.

Table 1: post-harvest soil parameters

S. No.	Particulars	Method used
1	Bulk density (Mg/m^{-3})	100 ml measuring cylinder method, Muthuvel *et al.*, (1992) [14]
2	Particle density (Mg/m^{-3})	
3	Pore space (%)	
4	Soil pH	Digital pH meter (Jackson, 1958)
5	Soil EC (dS/m)	Digital EC meter (Wilcox, 1950) [31]
6	Organic carbon (%)	Wet method (Walkley and Black' 1934) [30]
7	Available Nitrogen (N)	Alkaline permanganate method (Subbiah & Asija 1956) [26]
8	Available Phosphorus (P)	Calorimetric method (Olsen *et al.*, 1954) [15]
9	Available Potassium (K)	Flame photometric method (Toth and Prince, 1949) [28]
10	Available Zinc (Zn)	Spectrophotometer (Shaw and Dean 1952) [21]

Table 2: Effect of different level of NPK Zn and vermicompost on physical of soil after crop harvest

Treatment Details		Bulk density (Mg m^{-3})		Particle density (Mg m^{-3})		Pore space (%)	
		0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
T_1	RDF NPK Zn @ 0%+ V.C. @ 0%	1.29	1.32	2.59	2.61	41.25	39.47
T_2	RDF NPK Zn @ 0%+ V.C. @ 35%	1.28	1.31	2.57	2.57	44.05	42.28
T_3	RDF NPK Zn @ 0%+ V.C. @ 70%	1.27	1.29	2.50	2.50	44.44	43.80
T_4	RDF NPK Zn @ 0%+ V.C. @ 105%	1.26	1.26	2.55	2.55	45.57	42.10
T_5	RDF NPK Zn @ 50%+ V.C. @ 0%	1.24	1.25	2.55	2.55	43.87	42.55
T_6	RDF NPK Zn @ 50%+ V.C. @ 35%	1.27	1.27	2.52	2.52	44.78	44.64
T_7	RDF NPK Zn @ 50%+ V.C. @ 70%	1.26	1.27	2.55	2.55	46.23	44.17
T_8	RDF NPK Zn @ 50%+ V.C. @ 105%	1.27	1.27	2.54	2.56	46.53	42.26
T_9	RDF NPK Zn @ 100%+ V.C. @ 0%	1.26	1.27	2.52	2.52	44.31	42.73
T_{10}	RDF NPK Zn @ 100%+ V.C. @ 35%	1.26	1.28	2.54	2.54	47.31	46.39
T_{11}	RDF NPK Zn @ 100%+ V.C. @ 70%	1.24	1.25	2.53	2.53	50.21	48.16
T_{12}	RDF NPK Zn @ 100%+ V.C. @ 105%	1.24	1.26	2.59	2.53	48.44	45.25
'F' test		NS	NS	NS	NS	S	S
SE. d (±)		-	-	-	-	0.63	0.66
CV. (%)		-	-	-	-	2.40	2.62
$CD_{0.05}$		-	-	-	-	1.86	1.94

Table 3: Effect of different level of NPK Zn and vermicompost on chemical properties of soil after crop harvest

Treatment Details		Soil pH		Electrical conductivity (dS m^{-1})		Percent organic carbon (%)	
		0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
T_1	RDF NPK Zn @ 0%+ V.C. @ 0%	7.16	7.30	0.35	0.38	0.39	0.33
T_2	RDF NPK Zn @ 0%+ V.C. @ 35%	7.23	7.37	0.36	0.39	0.43	0.37
T_3	RDF NPK Zn @ 0%+ V.C. @ 70%	7.27	7.41	0.36	0.39	0.45	0.39
T_4	RDF NPK Zn @ 0%+ V.C. @ 105%	7.30	7.44	0.36	0.39	0.44	0.37
T_5	RDF NPK Zn @ 50%+ V.C. @ 0%	7.34	7.48	0.34	0.37	0.49	0.42
T_6	RDF NPK Zn @ 50%+ V.C. @ 35%	7.37	7.52	0.34	0.37	0.47	0.42
T_7	RDF NPK Zn @ 50%+ V.C. @ 70%	7.41	7.56	0.35	0.38	0.46	0.41
T_8	RDF NPK Zn @ 50%+ V.C. @ 105%	7.47	7.61	0.39	0.42	0.52	0.48
T_9	RDF NPK Zn @ 100%+ V.C. @ 0%	7.50	7.64	0.39	0.42	0.50	0.44
T_{10}	RDF NPK Zn @ 100%+ V.C. @ 35%	7.53	7.67	0.41	0.44	0.54	0.48
T_{11}	RDF NPK Zn @ 100%+ V.C. @ 70%	7.53	7.67	0.43	0.45	0.58	0.56
T_{12}	RDF NPK Zn @ 100%+ V.C. @ 105%	7.53	7.67	0.42	0.43	0.60	0.58
'F' test		NS	NS	NS	NS	S	S
SE. d (±)		-	-	-	-	0.02	0.02
CV. (%)		-	-	-	-	5.93	7.62
$CD_{0.05}$		-	-	-	-	0.05	0.05

Table 3: Effect of different level of NPK Zn and vermicompost on available nutrients of soil after crop harvest

Treatment Details		Available Nitrogen (kg ha^{-1})		Available Phosphorus (kg ha^{-1})		Available Potassium (kg ha^{-1})		Available Zinc (ppm ha^{-1})	
		0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
T_1	RDF NPK Zn @ 0%+ V.C. @ 0%	201.78	181.78	17.24	9.24	178.10	160.34	1.82	1.46
T_2	RDF NPK Zn @ 0%+ V.C. @ 35%	255.17	241.46	17.87	9.87	184.64	169.66	1.94	1.56
T_3	RDF NPK Zn @ 0%+ V.C. @ 70%	258.31	244.59	19.36	11.37	184.15	169.18	1.95	1.78
T_4	RDF NPK Zn @ 0%+ V.C. @ 105%	260.63	246.91	20.86	12.86	187.15	172.18	1.94	1.92
T_5	RDF NPK Zn @ 50%+ V.C. @ 0%	256.08	242.37	21.29	13.29	184.66	169.66	2.10	2.03
T_6	RDF NPK Zn @ 50%+ V.C. @ 35%	263.66	250.09	23.37	15.37	188.16	173.18	2.25	2.24
T_7	RDF NPK Zn @ 50%+ V.C. @ 70%	263.73	250.12	24.15	16.15	190.09	175.09	2.30	2.28
T_8	RDF NPK Zn @ 50%+ V.C. @ 105%	268.03	254.32	27.81	19.81	191.81	176.81	2.65	2.26
T_9	RDF NPK Zn @ 100%+ V.C. @ 0%	265.04	251.33	24.35	16.36	186.82	171.82	2.70	2.45
T_{10}	RDF NPK Zn @ 100%+ V.C. @ 35%	270.34	256.63	28.73	20.74	193.02	178.02	2.79	2.59
T_{11}	RDF NPK Zn @ 100%+ V.C. @ 70%	272.30	258.59	31.99	23.99	194.44	179.44	3.06	2.72
T_{12}	RDF NPK Zn @ 100%+ V.C. @ 105%	277.51	263.80	34.70	26.71	196.60	181.60	3.26	2.89
'F' test		S	S	S	S	S	S	S	S
SE. d (±)		0.87	1.00	0.82	0.82	0.61	0.93	0.06	0.06
CV. (%)		0.58	0.70	5.81	8.66	0.56	0.93	4.33	4.86
$CD_{0.05}$		2.55	2.92	2.39	2.39	1.79	2.76	0.18	0.18

Conclusion

The integrated application of RDF (Recommended Dose of Fertilizers) NPK Zn @ 100% combined with Vermicompost significantly influenced soil physico-chemical properties, growth, yield, and economic returns of mustard. Among all treatments, T_{11} (RDF NPK Zn @ 100% + Vermicompost @ 70%) consistently outperformed others. It recorded the lowest bulk and particle densities, and the highest values for pore space, water holding capacity, and electrical conductivity, indicating improved soil structure and fertility. In terms of nutrient status, T_{11} registered the highest levels of organic carbon, available nitrogen, phosphorus and potassium across 0-15 cm soil depths.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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