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Response of cumin to integrated organic and inorganic nutrient management on soil physico-chemical properties under Bundelkhand conditions

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ABSTRACT

A field experiment was conducted during the Rabi season of 2024–25 at the Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Bundelkhand University, Jhansi, Uttar Pradesh, to evaluate the effect of integrated organic and inorganic nutrient management on soil physical and chemical properties under cumin (*Cuminum cyminum* L.). The experiment was laid out in a Randomized Block Design (RBD) with eight treatments and three replications. The treatments consisted of different combinations of recommended dose of fertilizer (RDF), farmyard manure (FYM), vermicompost and biofertilizers, including Azotobacter and phosphate-solubilizing bacteria (PSB). Cumin variety GC-4 was used as the test crop. The initial soil was sandy loam in texture with bulk density of 1.36 g cm⁻³, particle density of 2.46 g cm⁻³, porosity of 44.71%, water-holding capacity of 32.00%, pH 7.43, organic carbon 0.32%, and available N, P and K of 151.00, 9.30 and 142.00 kg ha⁻¹, respectively. Integrated nutrient management substantially improved the physical condition and nutrient availability of the soil. The lowest bulk density (1.31 g cm⁻³), highest porosity (51.12%) and water-holding capacity (38.01%), together with the highest organic carbon (0.40%) and available potassium (159.50 kg ha⁻¹), were recorded under T₁ (75% RDF + 15 t FYM ha⁻¹). The highest available nitrogen (177.23 kg ha⁻¹) was observed under T₆ (125% RDF + 10 t vermicompost ha⁻¹), whereas the maximum available phosphorus (10.29 kg ha⁻¹) was recorded under T₇ (50% RDF + 50% FYM + Azotobacter + PSB). Particle density and soil pH showed non-significant treatment differences. Overall, the study demonstrated that the integration of organic manures with inorganic fertilizers improved soil physical properties and maintained better nutrient availability than sole application of inorganic fertilizer. Among the evaluated treatments, 75% RDF + 15 t FYM ha⁻¹ (T₁) emerged as a promising nutrient-management practice for improving overall soil health and sustaining soil fertility under cumin cultivation in the semi-arid conditions of Jhansi.

Keywords: Cumin, Integrated nutrient management, FYM, Vermicompost, Soil physical properties, Soil chemical properties, Available N, P and K, Soil fertility

Introduction

Cumin (*Cuminum cyminum* Linn.) is a traditional herbaceous plant, is a vital seed spice crop in arid and semi-arid regions. It belongs to the family Apiaceous and originating in northern Africa. Cumin is grown mainly in India, Iraq, Iran, Syria, Pakistan, Egypt, China, Turkey, Israel, and Italy. It is globally cultivated for its aromatic and medicinal properties (Dubey *et al.*, 2017) [1]. India is the largest producer and exporter of cumin, accounting for 70% of global production. Cumin was cultivated on approximately 11.45 lakh hectares, producing about 7.74 lakh tonnes of seed, with an estimated productivity of 676 kg ha⁻¹ (DASD, 2026). Rajasthan and Gujarat continue to be the principal cumin-producing states of the country. The latest Rajasthan accounted for approximately 10.82 lakh hectares with a production of 6.89 lakh tonnes, while Gujarat contributed about 4.77 lakh hectares with a production of 4.72 lakh tonnes during 2024–25 (Spices Board India, 2026) [2]. Cumin is generally grown on light-textured soils, where low organic matter, poor nutrient availability and inadequate moisture retention may constrain crop productivity. Adequate and balanced nutrition is therefore essential for optimum vegetative growth, branching, flowering, seed development and yield. Nitrogen is mainly associated with vegetative growth and chlorophyll formation, phosphorus with root development and reproductive processes, and potassium with water regulation, enzyme activation and translocation of assimilates. However, continuous dependence on inorganic fertilizers alone may not adequately maintain soil organic matter and physical quality. Consequently, integrated nutrient management (INM), involving the judicious combination of inorganic fertilizers, organic manures and biofertilizers, has gained importance as a sustainable approach to crop nutrition and soil fertility management (Mahajan *et al.*, 2023) [3]. Organic nutrient sources such as farmyard manure (FYM) supply nutrients gradually and add organic carbon to the soil, thereby improving aggregation, porosity, moisture retention and microbial activity.

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Soil organic carbon is an important indicator of soil quality and plays a central role in maintaining soil structure, nutrient availability and overall soil functioning (Singhal *et al.*, 2025) [4]. Vermicompost is another valuable organic amendment because of its nutrient-rich nature and favourable effects on soil physical, chemical and biological properties. Recent reviews have indicated that vermicompost can improve soil porosity, aeration, nutrient availability and water-holding capacity, while integrated application of organic and inorganic nutrient sources can improve soil quality and nutrient-use efficiency (Thirunavukkarasu *et al.*, 2023; Titirmare *et al.*, 2023; Yadav *et al.*, 2023) [5, 6, 7]. The quality and decomposition characteristics of organic carbon are influenced by the nature of plant residues and soil carbon pools Singhal *et al.*, (2026) [8]. Biofertilizers such as *Azotobacter* and phosphate-solubilizing bacteria (PSB) may further enhance nutrient cycling through biological nitrogen fixation and solubilization of otherwise unavailable soil phosphorus. Integration of organic manures with inorganic fertilizers improved cumin productivity and economic returns Patel *et al.* (2004) [9]. Cumin highest yield under integrated nutrient management involving FYM and biofertilizers Singh *et al.* (2006) [10]. In semi-arid conditions of Rajasthan significant effects of organic and inorganic nutrient sources on cumin soil fertility Shivran *et al.* (2017) [11]. The combinations involving vermicompost, inorganic fertilizer, *Azotobacter* and PSB improved cumin nutrient uptake Desai *et al.* (2020) [12].

Soil physical properties such as bulk density, particle density, porosity and water-holding capacity are important indicators of soil quality because they regulate root penetration, aeration, water movement and nutrient uptake. Similarly, soil pH, organic carbon and available nitrogen, phosphorus and potassium are important indicators of soil fertility and nutrient-supplying capacity. The application of organic materials in combination with fertilizers can improve these properties by increasing organic matter inputs, stimulating microbial activity and enhancing nutrient cycling. A recent review by Titirmare *et al.*, (2023) [6] concluded that combined application of organic manures and inorganic fertilizers can improve soil physical properties and sustain soil fertility more effectively than their separate use. Likewise, recent INM research has emphasized the simultaneous improvement of soil quality, nutrient availability and crop productivity through complementary use of organic, inorganic and biological nutrient sources (Mahajan *et al.*, 2023) [3].

The Bundelkhand region of Uttar Pradesh is characterized by variable rainfall, moisture limitations and constraints related to soil fertility, making maintenance of soil quality particularly important for sustainable crop production. Under such conditions, the incorporation of organic manures with recommended fertilizer doses and biofertilizers may provide an effective strategy for improving soil structure, water retention and nutrient availability. However, information regarding the comparative effects of FYM, vermicompost and biofertilizer-based nutrient combinations on soil physical and chemical properties under cumin in the Bundelkhand region is limited.

Materials and Methods

The field experiment was conducted during the *Rabi* season of 2024–25 at the Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Bundelkhand University, Jhansi, Uttar Pradesh, India. The experimental farm is situated at 25°27'37.5" N latitude and 78°36'15.6" E longitude, at an elevation of approximately 307 m above mean sea level. The region experiences tropical to subtropical climatic conditions, receiving an average annual rainfall of about 884.6 mm, of which nearly 90–95% is received during the south-west monsoon period from June to October, with two to three occasional showers during winter. Before initiation of the experiment, representative initial soil samples were collected from the experimental field at a depth of 0–15 cm using a soil auger from several randomly selected locations, thoroughly mixed to obtain a composite sample, air-dried, gently crushed and passed through a 2-mm sieve for physicochemical analysis. The experimental soil was sandy loam in texture and had a bulk density of 1.36 g cm⁻³, particle density of

2.46 g cm⁻³, porosity of 44.71% and water-holding capacity of 32.00%. The soil was neutral to slightly alkaline in reaction, with a pH of 7.43, and contained 0.32% organic carbon. The initial available nitrogen, phosphorus and potassium contents were 151.00, 9.30 and 142.00 kg ha⁻¹, respectively. Based on the initial soil test values, the soil was classified as low in available nitrogen and medium in available phosphorus and potassium, while the electrical conductivity was within the normal range and did not indicate any salinity problem. These initial soil properties were considered for assessing the response of cumin to different nutrient-management practices. The experiment was laid out in a Randomized Block Design (RBD) with eight treatments and three replications. The treatments comprised T₀: 100% recommended dose of fertilizer (RDF), T₁: 75% RDF + 15 t FYM ha⁻¹, T₂: 75% RDF + 15 t vermicompost ha⁻¹, T₃: 100% RDF + 15 t FYM ha⁻¹, T₄: 100% RDF + 15 t vermicompost ha⁻¹, T₅: 125% RDF + 10 t FYM ha⁻¹, T₆: 125% RDF + 10 t vermicompost ha⁻¹ and T₇: 50% RDF + 50% FYM + *Azotobacter* + PSB. Urea, diammonium phosphate (DAP) and muriate of potash (MOP) were used as sources of nitrogen, phosphorus and potassium, respectively. Cumin (*Cuminum cyminum* L.) variety GC-4 was used as the test crop and was sown manually using a seed drill on 14 November 2024 at a spacing of 22 cm between rows and 10 cm between plants. Before sowing, the seed was treated with Bavistin @ 2 g kg⁻¹ seed, shade-dried overnight and sown on the following day. Reseeding was carried out at 7 days after sowing (DAS) wherever gaps exceeding 10 cm were observed, while thinning was performed to maintain approximately 10 cm plant-to-plant spacing. Soil samples collected after sowing were analyzed for selected physical and chemical properties using standard analytical procedures. Bulk density was determined by the core method, while particle density was estimated using the pycnometer method, as described by Baruah *et al.* (1997) [13]. Soil porosity was calculated from the values of bulk density and particle density, whereas water-holding capacity was determined using the Keen-Raczowski box method following Baruah *et al.* (1997) [13]. Soil reaction (pH) was determined by the glass electrode method as described by Jackson (1958) [14]. Soil organic carbon was estimated by the wet oxidation method of Jackson (1973) [15]. Available nitrogen was determined by the alkaline permanganate method as outlined by Subbiah *et al.* (1956) [16], available phosphorus was estimated by the Olsen's method using a spectrophotometer (Olsen *et al.*, 1954) [17], and available potassium was determined using a flame photometer following extraction with neutral ammonium acetate (NH₄OAc), as described by Jackson (1973) [15]. The analytical results were used to assess the changes in soil physical and chemical properties following the application of different nutrient-management treatments. The experimental data were subjected to analysis of variance appropriate for Randomized Block Design following Gomez *et al.* (1984) [18]. The significance of treatment effects was tested at the 5% probability level.

Results and Discussion

Physical properties

The effect of different organic and inorganic nutrient-management practices on the physical and chemical properties of soil under cumin is presented in Table 1. The data revealed that nutrient-management treatments significantly influenced bulk density, porosity, water-holding capacity, available phosphorus and available potassium, whereas particle density, soil pH, organic carbon and available nitrogen were statistically non-significant. Nevertheless, considerable numerical variation was observed among the treatments, particularly for organic carbon and available nitrogen.

Bulk density (g cm⁻³)

The bulk density of soil varied from 1.31 to 1.36 g cm⁻³ among the different nutrient-management treatments. The lowest bulk density was recorded under T₁ (75% RDF + 15 t FYM ha⁻¹) at 1.31 g cm⁻³, representing a 3.68% decrease over the initial value of 1.36 g cm⁻³

and a 3.68% decrease over T_0 . This was followed by T_3 (1.32 g cm⁻³), T_2 and T_4 (1.33 g cm⁻³), which showed decreases of 2.94, 2.21 and 2.21%, respectively, over the initial soil value. The highest bulk density (1.36 g cm⁻³) was recorded under T_0 , which remained unchanged from the initial value. Treatments receiving FYM or vermicompost generally maintained lower bulk density than sole inorganic fertilization, indicating the beneficial influence of organic amendments on soil aggregation and pore development. The reduction in bulk density under FYM may be attributed to the addition of organic matter, which promotes aggregation and increases the proportion of pore spaces. Similar beneficial effects of integrated nutrient management involving FYM and vermicompost on soil fertility and crop performance in cumin have been reported by Shivran *et al.* (2017) [11]. Similar improvement in soil bulk density following vermicompost application has been reported by Parthasarathi *et al.* (2008) [19], who observed reduced bulk density in clay loam, sandy loam and red soils after vermicompost application.

Particle density (g cm⁻³)

Particle density after sowing ranged from 2.65 to 2.68 g cm⁻³, compared with 2.46 g cm⁻³ in the initial soil. The highest particle density (2.68 g cm⁻³) was observed in T_0 , T_1 and T_6 , corresponding to an 8.94% increase over the initial value. T_4 recorded 2.67 g cm⁻³, while T_7 recorded 2.67 g cm⁻³, representing increases of 8.54% over the initial value. The lowest value of 2.65 g cm⁻³ was recorded under T_3 , which was 7.72% higher than the initial value. The differences among treatments were statistically non-significant. Thus, although numerical variation occurred, nutrient management did not produce a significant effect on particle density. The general tendency of lower particle density following organic amendment has also been reported by Parthasarathi *et al.*, (2008) [19], who observed that vermicompost reduced both particle density and bulk density while improving soil physical condition.

Soil porosity (%)

Soil porosity increased considerably after application of the different nutrient-management treatments. The initial porosity was 44.71%, whereas post-sowing values ranged from 49.25 to 51.12%. The maximum porosity of 51.12% was recorded under T_1 , representing a 14.34% increase over the initial soil value and a 3.80% increase over T_0 . This was followed by T_3 and T_4 , both recording 50.19%, representing 12.26% increases over the initial value. T_2 and T_6 recorded 50.00%, corresponding to increases of 11.83% over the initial soil condition. The lowest post-sowing porosity was recorded in T_0 (49.25%), although this was still 10.15% higher than the initial value. The significant improvement in porosity may be associated with the incorporation of FYM and vermicompost, which promote soil aggregation, reduce compaction and increase pore space. Organic sources of nutrients are particularly beneficial for maintaining favourable soil physical conditions and improving the efficiency of nutrient use. Similar beneficial effects of organic and integrated nutrient management have been reported in cumin by Shivran *et al.*, (2017) [11].

Water-holding capacity (%)

Water-holding capacity increased under all treatments after sowing compared with the initial value of 32.00%, with values ranging from 35.60 to 38.01%. The maximum water-holding capacity was recorded under T_1 (75% RDF + 15 t FYM ha⁻¹) at 38.01%, representing an 18.78% increase over the initial soil value and a 6.77% increase over T_0 . T_3 recorded 37.86%, followed by T_2 (37.44%), T_4 (37.42%) and T_6 (37.12%), representing increases of 18.31, 17.00, 16.94 and 16.00%, respectively, over the initial soil condition. Even T_0 showed an 11.25% increase over the initial value. The improvement in water-holding capacity under organic-amended treatments may be attributed to increased organic matter, improved aggregation and greater development of micropores. FYM is particularly effective in improving soil moisture retention because its decomposition contributes to the formation of stable aggregates and increases the soil's capacity to retain water. The present observation is consistent with the established

benefits of organic nutrient sources reported for cumin production under semi-arid conditions.

Chemical properties

Soil pH

The soil pH decreased from the initial value of 7.43 to values ranging from 6.61 to 6.99 after sowing. The lowest pH of 6.61 was recorded under T_7 (50% RDF + 50% FYM + *Azotobacter* + PSB), representing an 11.04% decrease over the initial soil pH and a 4.48% decrease over T_0 . T_6 recorded a pH of 6.72, representing a 9.56% decrease from the initial value, while T_1 recorded 6.86, representing a 7.67% decrease. The highest pH after sowing was observed under T_2 (6.99), which was still 5.92% lower than the initial value. Although numerical differences occurred among treatments, the treatment effect was statistically non-significant. A similar decline in soil pH following organic amendment has been reported by Parthasarathi *et al.*, (2008) [19], who observed that vermicompost application reduced soil pH in different soil types.

Organic carbon (%)

Organic carbon was strongly influenced numerically by the incorporation of organic nutrient sources. The initial organic carbon content was 0.32%, while post-sowing values ranged from 0.24 to 0.40%. The highest organic carbon content of 0.40% was recorded under T_1 (75% RDF + 15 t FYM ha⁻¹), representing a 25.00% increase over the initial value and a substantial 33.33% increase over T_0 (0.30%). T_3 recorded 0.36%, which was 12.50% higher than the initial value and 20.00% higher than T_0 . T_2 recorded 0.33%, representing a 3.13% increase over the initial value. In contrast, T_6 recorded the lowest organic carbon content of 0.24%, representing a 25.00% decrease over the initial value. T_5 recorded 0.27%, a decrease of 15.62% over the initial value. The higher organic carbon under FYM-based treatments may be attributed to direct addition of decomposable organic material and subsequent accumulation of organic residues in soil. The importance of organic sources in improving soil fertility status under cumin has also been demonstrated by Shivran *et al.* (2017) [11], who reported higher soil organic carbon with organic nutrient sources.

Available nitrogen (kg ha⁻¹)

Available nitrogen after sowing ranged from 121.28 to 177.23 kg ha⁻¹, compared with 151.00 kg ha⁻¹ in the initial soil. The highest available nitrogen content of 177.23 kg ha⁻¹ was recorded under T_6 (125% RDF + 10 t vermicompost ha⁻¹), representing a 17.37% increase over the initial soil value and a 46.13% increase over T_0 . T_5 recorded 160.45 kg ha⁻¹, representing increases of 6.26% over the initial soil and 32.30% over T_0 . T_4 and T_3 recorded 155.65 and 150.32 kg ha⁻¹, respectively. T_0 recorded only 121.28 kg ha⁻¹, representing a 19.68% decrease from the initial value. The higher available nitrogen under vermicompost-based treatments may be attributed to continuous mineralization of organic nitrogen, improved microbial activity and better synchronization between nutrient release and crop demand. Shivran *et al.*, (2017) [11] also reported improved nitrogen availability and nitrogen balance under vermicompost-based nutrient management in cumin. These findings are supported by Raza *et al.*, (2022) [20], who highlighted that vermicomposting enhances nitrogen recovery and nutrient recycling and can contribute to improved soil fertility through stabilized organic nutrient sources.

Available phosphorus (kg ha⁻¹)

Available phosphorus ranged from 8.78 to 10.29 kg ha⁻¹ after sowing compared with the initial value of 9.30 kg ha⁻¹. The maximum available phosphorus content of 10.29 kg ha⁻¹ was recorded under T_7 (50% RDF + 50% FYM + *Azotobacter* + PSB), representing a 10.65% increase over the initial value and a 17.20% increase over T_0 . T_4 recorded 9.38 kg ha⁻¹, which was 0.86% higher than the initial value and 6.83% higher than T_0 . T_6 recorded 9.31 kg ha⁻¹, almost identical to the initial value, whereas T_0 recorded 8.78 kg ha⁻¹, representing a 5.59% decrease over the initial value. The improvement un

der T₇ may be attributed to the combined contribution of FYM, phosphorus fertilizer and phosphate-solubilizing bacteria, which can increase phosphorus mineralization and solubilization in the rhizosphere. The present findings are supported by Desai *et al.*, (2020) [12], who reported that integrated nutrient management involving vermicompost, fertilizer, Azotobacter and PSB significantly improved growth and productivity of cumin.

Available potassium (kg ha⁻¹)

Available potassium after sowing ranged from 136.41 to 159.50 kg ha⁻¹, compared with 142.00 kg ha⁻¹ in the initial soil. The highest available potassium content of 159.50 kg ha⁻¹ was recorded under T₁ (75% RDF + 15 t FYM ha⁻¹), representing a 12.32% increase over the initial soil value and a 16.93% increase over T₀. T₃ recorded 153.63 kg ha⁻¹, representing an 8.19% increase over the initial value, while T₂ recorded 151.32 kg ha⁻¹, representing a 6.56% increase. T₄, T₅ and T₆ also maintained available potassium at 149.32, 146.21 and 142.32 kg ha⁻¹, respectively. T₀ recorded 136.41 kg ha⁻¹, representing a 3.94% decrease from the initial value. The higher potassium availability under FYM treatment may be attributed to potassium release during decomposition of organic matter and improved soil ex-

change properties. Organic amendments can also improve nutrient retention and reduce nutrient losses, thereby maintaining a greater pool of plant-available potassium. The results are in agreement with Patel *et al.*, (2004) [9], who reported that integration of organic manures with inorganic fertilizers improved nutrient availability and productivity of cumin compared with individual nutrient sources.

Among the physical properties, T₁ was particularly effective in improving soil condition, recording the lowest bulk density (1.31 g cm⁻³), highest porosity (51.12%) and highest water-holding capacity (38.01%). Compared with the initial soil, these represented a 3.68% reduction in bulk density, 14.34% increase in porosity and 18.78% increase in water-holding capacity. Among the chemical properties, T₁ recorded the highest organic carbon (0.40%) and available K (159.50 kg ha⁻¹), T₆ recorded the highest available N (177.23 kg ha⁻¹), and T₇ recorded the highest available P (10.29 kg ha⁻¹). These results demonstrate that the integration of FYM/vermicompost with inorganic fertilizers improved the soil environment and nutrient availability compared with sole application of inorganic fertilizer. Similar beneficial effects of integrated nutrient management on cumin growth, productivity and soil fertility have been reported by Shivran *et al.*, (2017) [11], Patel *et al.*, (2004) [9] and Desai *et al.*, (2020) [12].

Table 1. Response of organic and inorganic nutrient management on physical-chemical properties of soil

Treatments	Physical properties				Chemical properties				
	Bulk density (g cm ⁻³)	Particle density (g cm ⁻³)	Porosity (%)	Water holding capacity (%)	Soil pH	Organic Carbon (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
Initial (Before sowing)	1.36	2.46	44.71	32.0	7.43	0.32	151	9.3	142
After sowing									
T ₀ (Control: 100% RDF)	1.36	2.68	49.25	35.6	6.92	0.30	121.28	8.78	136.41
T ₁ (75% RDF+ 15t/ha FYM)	1.31	2.68	51.12	38.01	6.86	0.40	135.32	9.11	159.50
T ₂ (75% RDF +15 t/ha vermicompost)	1.33	2.66	50.00	37.44	6.99	0.33	140.36	9.20	151.32
T ₃ (100% RDF+ 15t/ha FYM)	1.32	2.65	50.19	37.86	6.88	0.36	150.32	9.24	153.63
T ₄ (100% RDF + 15t/ha vermicompost)	1.33	2.67	50.19	37.42	6.94	0.30	155.65	9.38	149.32
T ₅ (125% RDF + 10t/ha FYM)	1.34	2.66	49.62	37.09	6.99	0.27	160.45	9.15	146.21
T ₆ (125% RDF + 10t/ha vermicompost)	1.34	2.68	50.00	37.12	6.72	0.24	177.23	9.31	142.32
T ₇ (50% RDF + 50% FYM + Azotobacter + PSB)	1.35	2.67	49.44	36.89	6.61	0.30	144.23	10.29	140.32
SEm±	0.01	0.02	0.34	0.21	0.11	0.02	2.06	0.24	4.34
CD (P = 0.05)	0.03	NS	1.04	0.64	NS	NS	NS	0.74	13.17

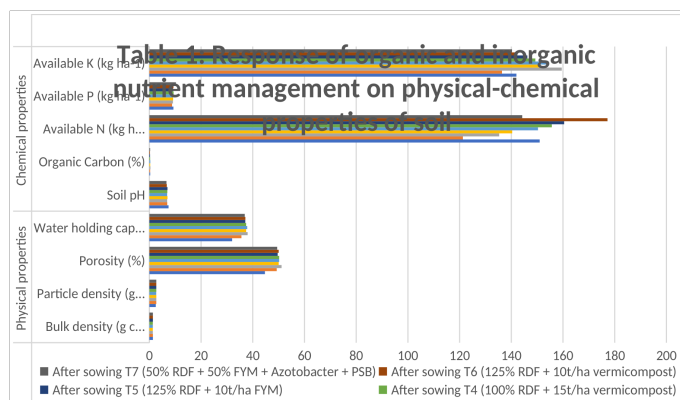
Conclusion

The study indicated that integrated nutrient management was more effective than sole application of inorganic fertilizer in improving soil physical condition and nutrient availability. Among the treatments, T₁ (75% RDF + 15 t FYM ha⁻¹) was particularly effective, recording the lowest bulk density (1.31 g cm⁻³), highest porosity (51.12%) and highest water-holding capacity (38.01%), along with the highest organic carbon (0.40%) and available potassium (159.50 kg ha⁻¹). The highest available nitrogen (177.23 kg ha⁻¹) was recorded under T₆ (125% RDF + 10 t vermicompost ha⁻¹), while the highest available phosphorus (10.29 kg ha⁻¹) was observed under T₇ (50% RDF + 50% FYM + Azotobacter + PSB). Particle density showed only minor variation among treatments and was statistically non-significant. Soil pH decreased from 7.43 initially to 6.61–6.99 after sowing, indicating a

favourable shift in soil reaction, although treatment differences were non-significant. Overall, the findings revealed that the combined use of organic manures and inorganic fertilizers improved soil structure, water retention, organic carbon status and availability of major nutrients compared with sole inorganic fertilization. Therefore, T₁ (75% RDF + 15 t FYM ha⁻¹) may be considered the most promising treatment for improving overall soil physical and chemical properties and maintaining soil fertility under cumin cultivation in the semi-arid conditions of Jhansi.

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