PLANT SCIENCE TODAY
Vol 13(sp1): 1-10
https://doi.org/10.14719/pst.12001

eISSN 2348-1900

RESEARCH ARTICLE

Crop-specific enriched vermicompost and its role in sustainable oilseed crop production

Anjali Bhargava[1*], Sanjay Kumar Sharma[1], Ankit Pandey[2], Manoj Kumar Tripathi[3] & Riya Mishra[3]

[1]Department of Soil Science, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya, Gwalior 474 002, Madhya Pradesh, India
[2]Kailash Nath Katju College of Horticulture, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya Mandsaur 458 001, Madhya Pradesh, India
[3]Department of Genetics and Plant Breeding, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya, Gwalior 474 002, Madhya Pradesh, India

*Correspondence email - anjalibhargava5@gmail.com

Received: 26 September 2025; Accepted: 02 February 2026; Available online: Version 1.0: 05 March 2026

Cite this article: Anjali B, Sanjay KS, Ankit P, Manoj KT, Riya M. Crop-specific enriched vermicompost and its role in sustainable oilseed crop production. Plant Science Today. 2026; 13(sp1): 1-10. https://doi.org/10.14719/pst.12001

Abstract

Organic farming has gained increasing attention in recent years due to growing concerns about soil health, environmental sustainability and consumer preference for safe and chemical-free food. Among various organic inputs, enriched vermicompost (EVC) has emerged as a promising alternative to chemical fertilisers, owing to its ability to improve soil fertility and crop productivity. The present study was undertaken to assess the effect of crop-specific enriched vermicompost on the growth and yield attributes of mustard (*Brassica juncea* L.) and sesame (*Sesamum indicum* L.). The experiment comprised three nutrient management treatments, viz., T_1, T_2 and T_3. Growth and yield parameters such as plant height, number of branches per plant, leaf area index, number of pods (capsules) per plant, protein content, oil content, root length density at harvest, shoot biomass (fresh and dry weight), test weight, seed yield, straw yield, biological yield and harvest index were recorded. The results revealed that all treatments performed statistically at par with respect to growth and yield attributes of both mustard and sesame. These findings indicate that crop-specific enriched vermicompost prepared using organic wastes, minerals and biofertilizers can potentially substitute chemical fertilisers without significant yield penalties. Thus, the use of enriched vermicompost in oilseed crops not only ensures sustainable yield but also contributes to soil health management and reduced dependency on synthetic inputs.

Keywords: enriched vermicompost; leaf area index; mustard; organic farming; root length density; sesame

Introduction

Oilseed crops hold a significant position in Indian agriculture, not only as a vital source of edible oils but also as an important contributor to nutritional security, industrial raw materials and livelihood generation for millions of farmers (1, 2). India ranks fifth globally in oilseed production and is among the largest consumers; however, domestic edible oil output consistently lags demand, leaving India heavily reliant on imports. Among the diverse oilseed crops cultivated, mustard (*Brassica juncea* L.) and sesame (*Sesamum indicum* L.) occupy a crucial niche due to their adaptability, economic value and nutritional importance (3–5). Mustard is the second most important oilseed crop after groundnut and is predominantly cultivated during the rabi season across northern and central India. Its oil is rich in essential fatty acids, while its seed meal serves as a protein-rich supplement in livestock feeding (6–9). "Sesame, the 'queen of oilseeds,' is characterised by high oil content (45–57 %), strong resistance to oxidative rancidity and medicinal value, which together make it a vital kharif crop in diverse regions of the country" (10, 11). Collectively, these crops play a pivotal role in strengthening the edible oil sector and supporting rural income (12, 13).

Despite their importance, the productivity of oilseed crops in India remains suboptimal compared to global standards. One of the primary reasons for this yield gap is the progressive decline in soil fertility, coupled with the imbalanced and indiscriminate use of chemical fertilisers (14, 15). The continuous application of recommended doses of fertilisers (RDF) alone often leads to nutrient mining, soil degradation and reduced organic carbon levels, which negatively impact soil health and long-term sustainability (16, 17). To counter these challenges, integrated nutrient management strategies that combine organic and inorganic sources of nutrients are gaining attention. Integrated approaches meet short-term crop nutrient demands while concurrently enhancing nutrient-use efficiency, soil physical properties and the functioning of beneficial soil microbial communities. (18, 19).

Enriched vermicompost (EVC) has emerged as a promising organic amendment in this context. Unlike ordinary compost, enriched vermicompost is fortified with essential nutrients such as phosphorus, sulfur and micronutrients (e.g., zinc, boron), along with beneficial microbial inoculants. This value addition enhances its ability to supply nutrients in a readily available form while simultaneously improving soil biological activity (20–22). Numerous studies indicate that the application of enriched vermicompost improves early crop establishment, root system development and nutrient acquisition, collectively contributing to enhanced yield and product quality. Moreover, when applied in combination with chemical fertilisers, enriched vermicompost can reduce the dependence on synthetic inputs while ensuring balanced nutrition and sustaining crop productivity (23–25).

Given the economic significance of mustard and sesame and the growing demand for sustainable nutrient management strategies, exploring the combined potential of enriched vermicompost and chemical fertilisers is of considerable importance. An approach that not only enhances crop yield but also conserves soil fertility and ensures environmental sustainability. However, field-based evidence on the long-term effects of such practices under contrasting cropping systems is still limited. Therefore, the present investigation was undertaken to assess the influence of enriched vermicompost, either applied alone or in combination with the recommended dose of fertilisers, on the growth, yield and nutrient uptake of mustard and sesame crops under the agro-climatic conditions of Madhya Pradesh.

The present study is novel in developing and evaluating *crop-specific enriched vermicompost* tailored to the nutrient requirements of oilseed crops. Unlike previous studies using generalised vermicompost, this work assesses targeted enrichment under field conditions over two consecutive seasons. The use of similar experimental plots enabled evaluation of residual and cumulative nutrient effects. Integration with recommended fertiliser doses further demonstrates its potential to reduce dependency on inorganic inputs while sustaining crop productivity.

Materials and Methods

Characteristics of the experimental site

The experiment was undertaken at the laboratory of the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya (RVSKVV), Gwalior, Madhya Pradesh, India. The experimental site is geographically positioned at 22°43′ N latitude and 76°54′ E longitude, with an elevation of 618 m above mean sea level (MSL). The location falls within a subtropical, semi-arid agro-climatic zone, characterised by hot, dry summers, cold winters and occasional rainfall events. The soil of the experimental field was relatively uniform in topography and fertility, thereby minimising spatial heterogeneity in edaphic conditions and ensuring the reliability of experimental observations.

Experimental setup and vermicomposting

Enriched vermicompost was prepared at the Animal Husbandry Farm, RVSKVV, Gwalior (Madhya Pradesh). The compost was produced using the earthworm species *Eisenia fetida* in cemented vermicompost pits available at the dairy farm (Fig. 1). A combination of different organic substrates along with mineral supplements, in T_3: Enrichment of VC through Neem cake + Wood ash + Gypsum + Poultry manure + Rock phosphate Azotobactor chroococume + *Bacillus polymixa* (PSB) + *Bacillus firmus* (K releasing bacteria) + *Trichoderma viridae* (Cellulolytic) was incorporated to enhance the nutrient content, particularly nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), calcium (Ca) and magnesium (Mg). The final composition of the enriched vermicompost is presented in Table 1. This enriched vermicompost was subsequently applied in the field experiment to assess its effect on mustard and sesame production (Fig.1).

Experimental details

Field experiments were conducted at the Research Farm, RVSKVV, Gwalior (Madhya Pradesh) during the kharif and rabi seasons of 2020, 2021 and 2022. The experimental layout followed a randomised block design (RBD) with seven replications and three treatments, resulting in a total of 21 plots. Each net plot measured 4.0 m × 3.0 m (12 m^2). The crop varieties used were mustard (NRCHB 101) during the rabi season and sesame (TKG 55) during the kharif season. Mustard was sown on 20 October 2020 and 23 October 2021, while sesame was sown on 16 July 2021 and 14 July 2022. Observations for mustard were recorded at 30, 60, 90 and 120 days after sowing, whereas observations for sesame were recorded at 30, 60 and at the time of harvesting. The experimental treatments consisted of three nutrient management practices: T_1–100 % enriched vermicompost (EVC), T_2–50 % enriched vermicompost + 50 % recommended dose of fertiliser (RDF) and T_3–100 % RDF. The recommended fertiliser dose for the sesame and mustard as per the treatments was applied (35:23:23 and 60:30:20 kg ha^{-1}. N, P_2O_5 and K_2O kg ha^{-1}, respectively) in the form of urea, single superphosphate and murate of potash, 5 cm away from the seed line and 5 cm deep in the soil. In all, 50 % of nitrogen and the entire dose of P_2O_5 and K_2O were applied at the time of sowing and the remaining 50 % of nitrogen was top-dressed in the form of urea, 30 days after sowing. In treatment 100 % NPK, P was added through DAP. As per treatment, vermicompost was added at 3.0 t $ha^{-1}yr^{-1}$ before sowing of oilseeds crop. The treatment $T_{3,}$ when applied at 3 t ha^{-1} can provide 60 kg ha^{-1} N, 42.9 kg ha^{-1} P_2O_5, 20.7 kg ha^{-1} K_2O, 39 kg ha^{-1} S and 25.50 mg Zn ha^{-1}. This content further increased due to the application of biofertilizers. These treatments were designed to assess the individual and combined effects of organic and inorganic nutrient sources on the growth, yield and nutrient uptake of mustard and sesame.

Physicochemical analysis of plant material

Sample collection and processing

After harvest, plant samples were collected from each plot for nutrient analysis. The samples were air-dried at room temperature, sequentially washed with 0.1 N HCl, then with

Table 1. Chemical composition of different enriched vermicompost at the end of decomposition

Treatment	pH (1:2.5)	EC (dSm^{-1})	TOC (%)	Total N (%)	Total P (%)	Total K (%)	Total S (%)	Total Zn (ppm)	Total Cu (ppm)	Total Fe (ppm)	Total Mn (ppm)	Total Ca (%)	Total Mg (%)	C:N Ratio
T_1	7.1	0.42	21	1.90	0.93	1.98	0.85	75	16	360	125	0.27	0.41	11.1
T_2	7.3	0.44	32.8	2.50	0.99	0.65	1.28	80	14	380	130	0.25	0.4	13.1
T_3	7.3	0.41	30.4	2.00	1.43	0.69	1.30	85	21	321	100	0.23	0.39	15.1
T_4	7.5	0.43	33.1	2.60	1.44	2.2	0.88	89	19	400	129	0.26	0.42	12.7
T_5	7.4	0.44	31.8	2.10	0.99	0.61	1.25	86	21	356	126	0.24	0.35	15.1
T_6	7.2	0.46	30.4	2.00	1.38	1.94	0.86	78	20	351	128	0.27	0.38	15.2
T_7	7.1	0.44	34.6	2.70	1.02	0.96	1.32	68	18	258	120	0.24	0.33	12.8
T_{15}	7.5	0.47	19.2	0.94	0.33	0.64	0.85	65	15	218	115	0.21	0.31	20.4
SEm±	0.11	0.01	0.603	0.12	0.047	0.018	0.027	2.05	1.24	1.15	1.22	0.011	0.014	1.0
$C.D_{5\%}$	0.33	0.041	1.83	0.37	0.150	0.05	0.08	6.22	3.77	3.47	3.71	0.03	0.04	3.0

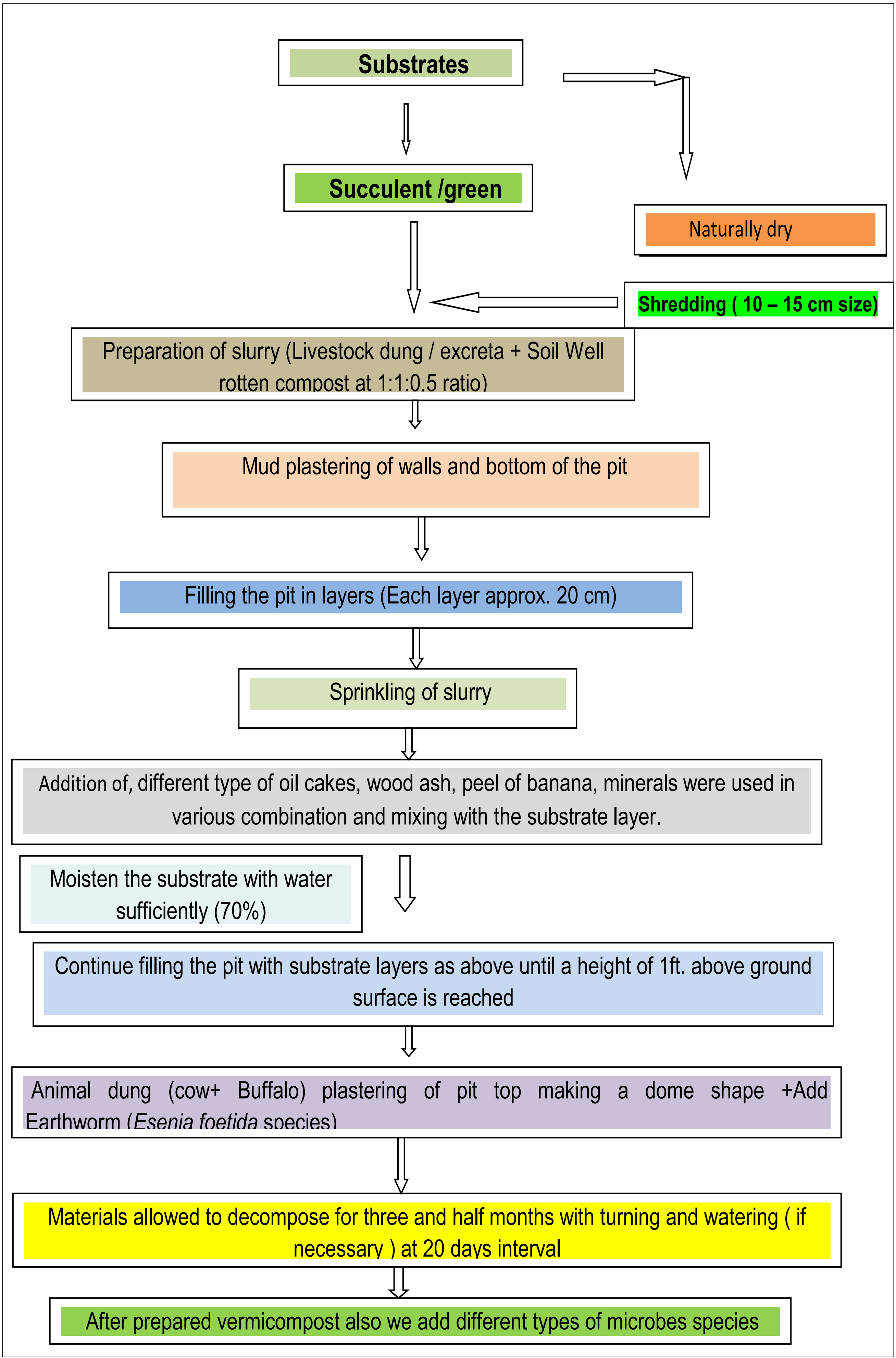

Fig. 1. Protocol used for preparation of enriched vermicompost.

demineralised water and oven-dried at 65 °C to a constant weight. The dried samples were ground using a Wiley mill equipped with stainless steel blades and passed through a sieve for uniform particle size.

Nutrient analysis

For nutrient estimation, the processed plant samples were subjected to wet digestion. For nitrogen (N), the total Kjeldahl nitrogen (TKN) content was determined using the standard Kjeldahl digestion and distillation method with a Kelplus Kjeldahl apparatus. For phosphorus (P) and potassium (K), the samples were digested using a di-acid mixture of HNO_3 and $HClO_4$. Phosphorus was estimated following the vanadomolybdate yellow colour method, while potassium was determined using a flame photometer (26, 27). Sulfur (S) concentration was measured using the digestion method, whereas micronutrients (Cu, Zn, Fe and Mn) were analysed using an atomic absorption spectrophotometer (AAS) following the DTPA-extraction method (28, 29).

pH and electrical conductivity (EC)

The pH and EC of the samples were determined using a substrate-to-water ratio of 1:10 (w/v). For this, 5 g of the sample was suspended in 50 mL of distilled water and shaken for 45 min. The suspension was filtered through Whatman filter paper and measurements were taken with a digital pH and conductivity meter (Systronics, 2551).

Statistical analysis

The data recorded during the investigation were analysed statistically using analysis of variance (ANOVA) for a randomised block design (RBD) as suggested by (30). The significance of treatment effects was assessed using an F-test at the 5 % level ($P \leq 0.05$). Data analysis was carried out using SPSS (statistical package for the social sciences) Software.

Results and Discussion

Mustard crop

Growth and yield attributes

The growth parameters of mustard as influenced by different nutrient management treatments are presented in Table 2. Plant height and leaf area index (LAI) recorded at successive growth stages (30, 60, 90 and 120 DAS) did not show statistically significant differences among treatments during individual years as well as in pooled analysis. However, a consistent numerical advantage was observed under the integrated application of 50 % enriched vermicompost (EVC) + 50 % recommended dose of fertilisers (RDF) (T_2), followed by 100 % EVC (T_1), whereas the lowest values were obtained with 100 % RDF (T_3). At 120 DAS, pooled plant height was maximum under T_2 (188.81 cm), which was marginally higher than T_1 (186.17 cm) and T_3 (183.43 cm). Similarly, LAI values at 90 DAS were highest in T_2 (3.31) compared to T_1 (3.20) and T_3 (3.12). This trend indicates that partial substitution of RDF with EVC supported better vegetative growth by improving nutrient release and availability throughout the crop growth period. Yield-attributing traits of mustard are summarised in Table 3. Although the treatment effects were found statistically non-significant, numerical superiority was again observed in T_2. Pooled data showed that plants under T_2 recorded 21.5 branches plant^{-1}, root length density of 0.103 cm cm^{-3} and 237.5 siliquae plant^{-1}, compared to 21.4, 0.084 cm $^{-1}$d 235.8 siliquae plant^{-1} in T_1 and 20.4, 0.066 cm cm^{-3} and 232.54 siliquae plant^{-1} in T_3, respectively. The higher branching and siliquae formation under EVC-integrated treatment may be attributed to a balanced supply of macro and

Table 2. Plant height (cm) and Leaf area Index different days after sowing (DAS) during Mustard growth period as influenced by different treatments

Treatment	30 DAS			60 DAS			90 DAS			120 DAS		
	Plant height											
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1: 100 % EVC	14.70	15.64	15.17	93.29	95.15	94.22	184.28	185.71	185.00	185.31	187.03	186.17
T_2:50 % EVC + 50 % RDF	15.90	16.47	16.19	94.73	94.98	94.85	186.37	187.80	187.09	188.23	189.39	188.81
T3: 100 % RDF	13.06	15.42	14.24	92.44	93.61	93.03	183.02	184.17	183.60	182.85	184.00	183.43
SEm±	1.23	0.38	0.64	0.91	0.89	0.64	1.11	2.13	1.20	2.47	2.72	1.84
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Leaf area index											
T_1: 100 % EVC	0.336	0.347	0.341	2.16	2.24	2.20	3.19	3.20	3.20	0.996	1.007	1.001
T_2:50 % EVC + 50 % RDF	0.349	0.350	0.349	2.21	2.39	2.30	3.29	3.34	3.31	1.001	1.109	1.055
T_3: 100 % RDF	0.327	0.334	0.331	2.07	2.14	2.10	3.08	3.16	3.12	0.966	0.999	0.982
SEm±	0.007	0.007	0.006	0.10	0.09	0.07	0.07	0.05	0.04	0.015	0.034	0.023
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 3. Yield attributing characters of Mustard as influenced by different treatments at the harvesting of crop

Treatment	Branches plant^{-1} at harvest time			Root length density (cm cm^{-3}) at harvest time			Number of Siliqua plant^{-1}			Protein content (%)		
	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled
T_1: 100 % EVC	20.9	21.9	21.4	0.077	0.092	0.084	233.90	237.70	235.80	21.41	22.78	22.09
T_2: 50 % EVC + 50 % RDF	21.0	22.0	21.5	0.096	0.110	0.103	236.30	238.70	237.50	22.21	23.09	22.65
T_3: 100 % RDF	19.9	20.8	20.4	0.055	0.077	0.066	230.08	235.01	232.54	21.00	22.50	21.75
SEm±	0.58	0.37	0.34	0.014	0.018	0.021	3.83	1.60	2.07	0.42	0.34	0.27
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Treatment	Shoot dry weight plant^{-1} (g)			Shoot fresh weight plant^{-1} (g)			Test weight (g)			Oil content (%)		
	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled
T_1: 100 % EVC	7.26	7.51	7.39	142.1	143.0	142.57	4.88	5.02	4.95	37.42	38.28	37.85
T_2: 50 % EVC + 50 % RDF	7.78	7.78	7.78	143.6	144.1	143.89	5.02	5.17	5.09	38.22	39.01	38.61
T_3: 100 % RDF	7.24	7.47	7.35	141.1	142.6	141.92	4.49	4.92	4.70	36.65	37.69	37.17
SEm±	0.23	0.10	0.13	1.19	1.18	0.84	0.19	0.09	0.10	0.69	0.73	0.50
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

micro-nutrients, improved root proliferation and better physiological activity.

Seed quality parameters such as protein and oil content also followed the same trend. Pooled data revealed that T_2 resulted in the highest protein content (22.65 %) and oil content (38.61 %), followed by T_1 (22.09 % and 37.85 %, respectively), whereas T_3 recorded the lowest values (21.75 % and 37.17 %). Similarly, shoot biomass (fresh and dry weight) and test weight were superior in T_2 compared to T_1 and T_3. Increased protein and oil accumulation under EVC-integrated treatments may be associated with improved mineralisation and with the synchronised availability of nitrogen and sulfur, nutrients directly involved in protein synthesis and oil biosynthetic pathways in mustard. Aligning with the above results, (31) reported that the combined application of sulphur and vermicompost resulted in the maximum plant height, number of leaves and branches. These improvements were primarily attributed to enhanced photosynthetic efficiency and better nutrient assimilation. Furthermore, Research has demonstrated that the integration of vermicompost with inorganic fertilisers significantly increased plant height, leaf area and biomass production, owing to improved soil nutrient availability and enhanced water-holding capacity (32). Sequential Pak-Coi mustard cropping evaluated three types of vermicompost (spent mushroom waste, coconut husk, sugarcane trash) at 5-20 t ha^{-1}were noticed (33). Vermicompost application improved soil NPK and nutrient uptake, with the highest yield in the first cropping observed for V_1 and V_2 at 10–15 t ha^{-1}. Residual effects increased yield in the second cropping, while productivity declined in the third and fourth, varying by vermicompost type. Overall, although the observed differences were not statistically significant, the integrated use of 50 % EVC + 50 % RDF (T_2) consistently produced better growth, yield-attributing traits and seed quality parameters compared to the sole application of either EVC (T_1) or RDF (T_3). These results demonstrate that integrating enriched vermicompost with inorganic fertilisers exerts a synergistic effect on mustard productivity by improving soil fertility, nutrient-use efficiency, crop growth and performance.

Yield

The effect of different nutrient management practices on seed yield, stover yield, biological yield and harvest index of mustard is presented in Table 4. Although the differences among treatments were statistically non-significant during both years, as well as in pooled data, a clear trend of improvement was observed with the integrated application of enriched vermicompost (EVC) and recommended dose of fertilisers (RDF). The pooled seed yield was highest under 50 % EVC + 50 % RDF (T_2) with 1617.9 kg ha^{-1}, followed by 100 % EVC (T_1, 1459.3 kg ha^{-1}) and 100 % RDF (T_3, 1441.8 kg ha^{-1}). Similarly, stover yield was superior in T_2 (5490.9 kg ha^{-1}), while slightly lower values were recorded in T_1 (5135.8 kg ha^{-1}) and T_3 (4998.4 kg ha^{-1}). The higher seed and stover yields under T_2 resulted in the maximum biological yield (7047.7 kg ha^{-1}), compared with 6638.7 kg ha^{-1} in T_1 and 6457.7 kg ha^{-1} in T_3. The harvest index (HI) varied marginally among treatments, with pooled values ranging from 20.92 % in T_1 to 21.68 % in T_2. Although not statistically significant, the relatively higher HI in T_2 indicates more efficient partitioning of assimilates towards the economic sink under integrated nutrient management.

Similar results have been reported by 34, 35 and 36. Research has demonstrated that vermicompost (0–6 t ha^{-1}) and fertility levels (0–100 % RDF) on Indian mustard (34). Application of 6 t ha^{-1} vermicompost and 100 % RDF individually improved yield attributes, seed yield and economic returns. The combined use of 6 t ha^{-1} vermicompost with 100 % RDF produced the highest seed yield (24.87 q ha^{-1}) and maximum gross and net returns, demonstrating a synergistic effect (34). Field experiments across three agroecological zones showed that combining vermicompost with reduced chemical fertilisers improved mustard growth, yield and nutrient uptake (35). Treatments with 75 % CF + 4 t ha^{-1} vermicompost or 85 % CF + 2 t ha^{-1} vermicompost produced yields comparable to 100 % CF. Thus, 15–25 % of chemical fertiliser can be safely reduced using vermicompost without compromising mustard productivity (35). Overall, the results revealed that the combined application of 50 % EVC and 50 % RDF consistently enhanced seed yield, stover yield and biological yield compared to the sole application of either EVC or RDF. The improvement under T_2 may be attributed to the synergistic effect of organic and inorganic nutrient sources, wherein enriched vermicompost not only improves soil structure and microbial activity but also complements the nutrient supply from chemical fertilisers, thereby sustaining mustard productivity (36).

Nutrient uptake

The uptake of major nutrients (N, P, K, S and Zn) by mustard crop as influenced by different treatments is presented in Table 5. Although the differences among treatments were statistically non-significant, a consistent trend was observed across both years and in the pooled data. Nutrient uptake through seed was found to be highest under 50 % EVC + 50 % RDF (T_2), recording pooled values of 37.78 kg ha^{-1} N, 9.22 kg ha^{-1} P, 9.61 kg ha^{-1} K, 12.49 kg ha^{-1} S and 53.92 g ha^{-1} Zn. This was followed by 100 % EVC (T_1), which showed pooled seed uptake of 33.09 kg ha^{-1} N, 8.12 kg ha^{-1} P, 8.53 kg ha^{-1} K, 10.97 kg ha^{-1} S and 47.07 g ha^{-1} Zn. The lowest nutrient uptake through seed was observed under 100 % RDF (T_3), with pooled values of 29.74 kg ha^{-1} N, 7.90 kg ha^{-1} P, 8.29 kg ha^{-1} K, 10.83 kg ha^{-1} S and 45.07 g ha^{-1} Zn.

Despite consistent numerical improvements in growth, yield and nutrient uptake under integrated application of enriched

Table 4. Grain, stover yield and harvest index (HI) of mustard influenced by different treatments

Treatment	Seed yield (kg ha^{-1})			Stover yield (kg ha^{-1})		
	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled
T_1: 100 % EVC	1287.9	1630.7	1459.3	4683.4	5588.2	5135.8
T_2:50 % EVC + 50 % RDF	1486.4	1749.3	1617.9	5271.5	5710.4	5490.9
T_3: 100 % RDF	1257.3	1626.3	1441.8	4611.5	5385.3	4998.4
SEm±	96.8	92.9	67.1	359.1	347.4	249.8
CD (5 %)	NS	NS	NS	NS	NS	NS

Treatment	Biological yield (kg ha^{-1})			Harvest index (%)		
	2020-21	2021-22	Pooled	2020-21	2021-22	Pooled
T_1: 100 % EVC	5940.7	7336.6	6638.7	21.20	20.63	20.92
T_2:50 % EVC + 50 % RDF	6758.0	7337.5	7047.7	22.11	21.26	21.68
T_3: 100 % RDF	5899.4	7016.0	6457.7	21.96	20.81	21.38
SEm±	449.6	436.3	313.3	0.46	0.63	0.39
CD (5 %)	NS	NS	NS	NS	NS	NS

Table 5. Effect of different treatments on the total nutrient uptake in the mustard crop

Treatment	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})			S (kg ha^{-1})			Zn (g ha^{-1})		
Nutrient uptake by the seed															
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1: 100 % EVC	27.19	39.00	33.09	6.88	9.36	8.12	6.58	10.49	8.53	8.68	13.25	10.97	37.51	56.50	47.07
T_2:50 % EVC + 50 % RDF	31.40	44.15	37.78	8.07	10.37	9.22	7.85	11.38	9.61	10.61	14.36	12.49	44.94	62.90	53.92
T_3: 100 % RDF	23.50	35.98	29.74	6.63	9.17	7.90	6.26	10.32	8.29	8.55	13.11	10.83	36.17	53.98	45.07
SEm±	3.85	3.26	2.52	0.46	0.57	0.36	0.65	0.58	0.43	0.83	0.94	0.63	2.99	4.31	2.62
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Nutrient uptake by stover															
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1: 100 % EVC	15.03	17.86	16.45	5.12	6.63	5.87	49.18	65.62	57.40	16.66	21.01	18.83	47.17	66.97	57.07
T_2:50 % EVC + 50 % RDF	17.55	19.17	18.36	6.31	7.16	6.74	58.48	72.73	65.60	19.45	22.05	20.75	55.88	69.46	62.67
T_3: 100 % RDF	14.04	16.80	15.42	4.91	6.05	5.48	48.16	62.63	55.40	16.15	20.12	18.14	45.76	62.45	54.11
SEm±	1.46	1.22	0.95	0.45	0.72	0.48	3.87	6.55	3.81	1.39	1.38	0.98	3.62	5.06	2.97
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

vermicompost (EVC) and inorganic fertilisers, treatment effects were statistically non-significant across seasons. This limited statistical differentiation may be due to the relatively high baseline soil fertility, which likely attenuated treatment contrasts, along with the slow mineralisation and gradual nutrient-release characteristics of EVC. Seasonal environmental variability may have further moderated treatment responses. Nonetheless, the reproducible numerical trends, particularly the modest yield enhancement observed in the second year, indicate a possible cumulative or residual effect of EVC that may manifest more clearly over longer experimental durations. Compared with earlier studies reporting larger yield gains under integrated nutrient management (37, 38), the smaller response magnitude observed here suggests that EVC may contribute more to nutrient-use efficiency and soil quality stabilisation than to immediate yield maximisation. From a sustainability perspective, these incremental gains, coupled with reduced dependence on mineral fertilisers, remain agronomically and environmentally relevant.

Similarly, nutrient uptake by stover also followed a comparable trend. The maximum pooled uptake was recorded under T_2 (50 % EVC + 50 % RDF) with 18.36 kg ha^{-1} N, 6.74 kg ha^{-1} P, 65.60 kg ha^{-1} K, 20.75 kg ha^{-1} S and 62.67 g ha^{-1} Zn. Treatments T_1 (100 % EVC) and T_3 (100 % RDF) showed relatively lower nutrient uptake through stover, with pooled values of 16.45 and 15.42 kg ha^{-1} N, 5.87 and 5.48 kg ha^{-1} P, 57.40 and 55.40 kg ha^{-1} K, 18.83 and 18.14 kg ha^{-1} S and 57.07 and 54.11 g ha^{-1} Zn, respectively. Overall, the integration of enriched vermicompost with the recommended fertiliser dose (T_2) consistently enhanced nutrient uptake in both seed and stover as compared to the sole application of either enriched vermicompost or RDF. This suggests a complementary effect of organic and inorganic nutrient sources in improving nutrient assimilation and partitioning in the mustard crop.

Sesame crop

Growth and yield attributes

The growth and yield attributes of sesame as influenced by different nutrient management treatments are presented in Table 6 &7. Plant height increased progressively with crop age across all treatments, with the highest values consistently observed under the integrated application of 50 % enriched vermicompost + 50 % RDF (T_2). At harvest, pooled plant height reached 122.0 cm under T_2, compared with 120.0 cm under 100 % EVC (T_1) and 116.9 cm under 100 % RDF (T_3). Although the differences were statistically non-significant, the trend indicated a slight superiority of the integrated treatment. Similarly, the leaf area index (LAI) was highest under T_2 (1.3 at 30 DAS, 3.2 at 60 DAS and 3.1 at harvest), followed by T_1 and T_3. These findings suggest that balanced nutrient availability through integrated use of organic and inorganic sources provided a favourable environment for sustained vegetative growth and canopy development.

Yield-attributing traits also reflected this pattern. The number of branches per plant at harvest was highest under T_2 (21.0), marginally higher than T_1 (20.7) and T_3 (20.5). The number of capsules per plant showed similar improvement with T_2 (7.2) compared to 6.4 under T_1 and 6.6 under T_3. Shoot biomass accumulation followed the same trend, with T_2 recording the maximum shoot fresh (51.2 g plant^{-1}) and dry weight (8.2 g plant^{-1}). Root length density was also marginally higher under T_2 (0.34 cm cm^{-3}), suggesting better root development and nutrient uptake efficiency. Quality parameters of sesame seed, namely protein and oil content, exhibited slight improvement under integrated nutrient application. The pooled protein content was 23.1 % under T_2, compared with 22.4 % in T_1 and 21.8 % in T_3. Oil content followed a similar trend, with the maximum value recorded under T_2 (44.6 %), slightly higher than T_1 (43.3 %) and T_3 (43.2 %). Although these differences did not attain statistical significance, the consistent

Table 6. Plant height (cm) and Leaf area index on different days after sowing (DAS) during the sesame growth periods

Treatment	30 DAS			60 DAS			At harvest		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
Plant height									
T_1: 100 % EVC	46.3	49.0	47.6	67.6	74.3	70.9	116.0	124.0	120.0
T_2:50 % EVC + 50 % RDF	48.6	50.8	49.7	69.7	76.8	72.1	119.6	125.9	122.0
T_3: 100 % RDF	44.1	48.9	46.5	63.8	74.0	68.9	109.9	123.9	116.9
SEm±	1.24	0.64	0.28	1.63	1.04	0.92	3.08	1.18	1.65
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS
Leaf area index									
T_1: 100 % EVC	1.1	1.4	1.2	3.0	3.2	3.1	3.0	3.0	3.0
T_2:50 % EVC + 50 % RDF	1.2	1.5	1.3	3.1	3.3	3.2	3.1	3.0	3.0
T_3: 100 % RDF	0.9	1.3	1.1	2.9	3.1	3.0	2.9	2.9	2.9
SEm±	0.09	0.08	0.06	0.07	0.06	0.09	0.07	0.072	0.04
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 7. Different growth, yield attribute and quality parameter of Sesame Crop.

Treatment	No. of Branchesplant^{-1} at harvest time			No. of pods (capsule) plant $^{-1}$			Shoot fresh weight plant^{-1} (g)			Shoot dry-weight plant^{-1} (g)		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1: 100 % EVC	19.8	21.7	20.7	6.4	6.4	6.4	45.5	52.1	48.8	6.4	8.9	7.7
T_2:50 % EVC + 50 % RDF	20.2	21.7	21.0	7.2	7.2	7.2	49.2	53.2	51.2	7.2	9.1	8.2
T_3: 100 % RDF	19.7	21.4	20.5	6.6	6.6	6.6	44.2	52.0	48.1	6.6	8.7	7.7
SEm±	0.88	0.87	0.62	0.32	0.32	0.32	1.44	0.69	0.80	0.32	0.11	0.16
CD $_{(5\,\%)}$	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Treatment	Test weight (g)			Root length density at harvest time (cm cm^{-3})			Protein content (%)			Oil content %		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1: 100 % EVC	2.6	2.6	2.6	0.34	0.35	0.34	22.1	22. 8	22.4	43.7	43.0	43.3
T_2:50 % EVC + 50 % RDF	2.9	2.7	2.8	0.34	0.35	0.34	22.5	23.7	23.1	44.1	45.1	44.6
T_3: 100 % RDF	2.4	2.6	2.5	0.32	0.32	0.33	20.7	22.7	21.8	42.8	43.6	43.2
SEm±	0.15	0.10	0.13	0.007	0.009	0.006	0.63	0.58	0.43	0.92	0.88	1.29
CD $_{(5\,\%)}$	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

positive effect of T_2 across growth, yield and quality traits highlights the benefits of combining enriched vermicompost with chemical fertilizers. The integrated approach likely enhanced nutrient synchronisation, soil biological activity and overall plant metabolism, which translated into improved performance over sole organic or inorganic nutrient sources.

Similarly, research indicates that applying 100 % RDN through farmyard manure (FYM) with silicon at 200 kg ha^{-1} significantly improved growth, yield, nutrient uptake and quality of sweet corn under organic farming (39). Lower FYM rates (75 % RDN) also performed well, while 50 % RDN combined with silicon maximised nitrogen use efficiency. These findings indicate that integrating organic nitrogen sources with silicon can optimise productivity and nutrient efficiency in organic sweet corn cultivation (39). Research showed that integrated nutrient management combining 100 % RDF with 75 % RDN through FYM, vermicompost and neem oil cake improved growth, yield attributes, seed, stover and oil yield (40). Research has demonstrated that integrating vermicompost (15 t ha^{-1}) with 70 % RDF significantly enhanced growth, yield attributes and 1000-seed weight compared to the control. Nutrient concentrations (N, P, K, S, Fe, Zn) and seed protein content were also highest under this treatment (41). These results indicate that combining organic and inorganic fertilisers improves sesame productivity and seed quality (41).

Yield

The seed, stover and biological yields of sesame as influenced by different nutrient management practices are presented in Table 8. Despite the absence of statistically significant differences among treatments, the integrated application of 50 % enriched vermicompost + 50 % RDF (T_2) consistently exhibited higher productivity. The pooled seed yield under T_2 was 625.8 kg ha^{-1}, which was higher than 580.2 kg ha^{-1} under 100 % EVC (T_1) and 573.3 kg ha^{-1} under 100 % RDF (T_3). Similarly, pooled stover yield was recorded at 1187.6 kg ha^{-1} under T_2, compared with 1174.6 kg ha^{-1} and 1170.6 kg ha^{-1} under T_1 and T_3, respectively. Biological yield also followed a similar pattern, with the maximum pooled value of 1813.5 kg ha^{-1} under T_2, slightly higher than T_1 (1754.9 kg ha^{-1}) and T_3 (1743.9 kg ha^{-1}). The harvest index (HI) ranged from 32.8 % to 34.4 %, with the highest value observed under T_2 (34.4 %). This indicates that integrated nutrient application not only improved total biomass production but also contributed to a more efficient partitioning of assimilates towards economic yield.

Research evaluated intercropping systems of mungbean, mothbean and sesame under integrated nutrient management. Sole crops recorded higher seed and straw yields than 2:1 paired-row intercropping, while 50 % RDF through fertiliser + 50 % RDF through vermicompost significantly improved yield attributes and overall productivity across all crops (42). Sesame in coastal saline soil demonstrated that integrating vermicompost with 50 % soil-applied $ZnSO_4$ + $MnSO_4$ and foliar sprays of $ZnSO_4$ + $MnSO_4$ (0.5 %) significantly enhanced growth, seed (792 kg ha^{-1}) and stalk yield (1713 kg ha^{-1}) and nutrient uptake (43). This treatment increased seed and stalk yield by 45.3 % and 36.8 %, respectively, over RDF alone. Although the yield differences were not statistically significant, the consistent superiority of T_2 over sole organic (T_1) or sole inorganic fertilisation (T_3) suggests that the integrated use of enriched vermicompost with chemical fertilisers ensured better nutrient availability and synchronisation with crop demand. This may have enhanced physiological processes and yield stability of sesame under field conditions, thereby supporting the role of integrated nutrient management in sustaining productivity.

Nutrient uptake

Table 8. Grain, stover yield and Harvest Index (HI) of Sesame influenced by different treatments.

Treatment	Seed yield (kg ha^{-1})			Stover yield (kg ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled
T_1: 100 % EVC	551.8	608.7	580.2	1149.2	1200.0	1174.6
T_2:50 % EVC + 50 % RDF	601.5	650.1	625.8	1167.4	1207.9	1187.6
T_3: 100 % RDF	544.2	602.4	573.3	1143.4	1197.7	1170.6
SEm±	33.99	18.39	19.32	23.1	24.4	16.8
CD $_{(5\,\%)}$	NS	NS	NS	NS	NS	NS

Treatment	Biological yield (Kg ha^{-1})			Harvest Index (%)		
	2021	2022	Pooled	2021	2022	Pooled
T_1: 100 % EVC	1701.1	1808.7	1754.9	32.1	33.6	32.9
T_2:50 % EVC + 50 % RDF	1769.0	1858.0	1813.5	33.9	34.9	34.4
T_3: 100 % RDF	1687.7	1800.1	1743.9	32.2	33.5	32.8
SEm±	46.2	24.0	26.0	1.31	0.94	0.81
CD $_{(5\,\%)}$	NS	NS	NS	NS	NS	NS

The nutrient uptake of sesame seed and straw under different nutrient management practices is presented in Table 9. Although treatment differences were statistically non-significant, a consistent trend of higher nutrient uptake was recorded with the integrated application of 50 % enriched vermicompost + 50 % RDF (T_2). For seed nutrient uptake, pooled data indicated maximum nitrogen uptake (19.40 kg ha^{-1}) in T_2, compared with 16.91 kg ha^{-1} in 100 % EVC (T_1) and 15.45 kg ha^{-1} in 100 % RDF (T_3). A similar pattern was observed for phosphorus (3.98 kg ha^{-1}), potassium (4.19 kg ha^{-1}), sulfur (2.79 kg ha^{-1}) and zinc (31.84 g ha^{-1}), all of which were highest under T_2. Treatments T_1 and T_3, despite treatment-wise differences in nutrient uptake by seed and straw, the observed increases were largely statistically non-significant across seasons. This lack of clear statistical separation may be attributed to the relatively adequate baseline soil fertility, which could have buffered treatment effects, as well as the nutrient composition and gradual mineralisation pattern of enriched vermicompost (EVC). Environmental variability between seasons may have further moderated nutrient assimilation responses. Nevertheless, integrated nutrient management (T_2) consistently recorded numerically higher nutrient uptake in straw, with pooled values of N (12.01 kg ha^{-1}), P (5.40 kg ha^{-1}), K (11.06 kg ha^{-1}), S (4.93 kg ha^{-1}) and Zn (28.39 g ha^{-1}), whereas sole RDF (T_3) showed the lowest uptake and 100 % EVC (T_1) remained intermediate. The reproducibility of these trends across years suggests a cumulative improvement in nutrient-use efficiency and internal nutrient cycling rather than an immediate yield-driven response. Research indicates that larger increases in nutrient uptake under integrated nutrient management (44–46). The relatively modest gains may represent a more conservative but environmentally efficient strategy, offering potential long-term benefits in soil nutrient availability and reduced reliance on mineral fertilisers.

Conclusion

The present study indicated that the application of integrated nutrient management involving partial substitution of inorganic fertilisers with enriched vermicompost resulted in positive trends in growth, yield and nutrient uptake of mustard and sesame under semi-arid conditions. Integrated nutrient management involving partial substitution of inorganic fertilizers with enriched vermicompost consistently performed better across both years. These trends suggest improved nutrient-use efficiency and crop performance under integrated nutrient application. The study highlights the potential of enriched vermicompost as a complementary nutrient source for sustainable oilseed production; however, long-term investigations including soil health indicators are required to substantiate its sustainability benefits.

Authors' contributions

AB and RM are responsible for drafting and writing the manuscript. MKT, SKS and AP contributed to the conceptualization of the study and provided essential project supervision and instrumental in the preparation of the research framework. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Table 9. Effect of different treatments on the nutrient uptake in the sesame crop

Treatment	Nutrient uptake by seed														
	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})			S (kg ha^{-1})			Zn (g ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1: 100 % EVC	15.66	18.16	16.91	3.34	3.86	3.60	3.56	4.08	3.82	2.34	2.68	2.51	27.09	30.45	28.77
T_2:50 % EVC + 50 % RDF	18.52	20.28	19.40	3.70	4.26	3.98	3.98	4.40	4.19	2.70	2.89	2.79	30.25	33.42	31.84
T_3: 100 % RDF	14.20	16.70	15.45	3.18	3.78	3.48	3.44	3.95	3.70	2.21	2.54	2.37	26.28	30.02	28.15
SEm±	1.50	1.45	1.35	0.24	0.53	0.18	0.21	0.18	0.18	0.19	0.15	0.18	1.59	0.98	0.93
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Nutrient uptake by straw														
Treatment	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})			S (kg ha^{-1})			Zn (g ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1: 100 % EVC	11.19	11.91	11.55	4.82	5.32	5.07	10.19	11.32	10.76	4.49	5.12	4.81	26.53	27.76	27.15
T_2:50 % EVC + 50 % RDF	11.59	12.42	12.01	5.24	5.66	5.40	10.63	11.49	11.06	4.68	5.19	4.93	27.75	29.03	28.39
T_3: 100 % RDF	11.03	11.63	11.33	4.71	5.12	4.92	9.97	11.16	10.56	4.27	5.09	4.68	25.12	27.28	26.20
SEm±	0.28	0.36	0.23	0.19	0.24	0.15	0.32	0.28	0.21	0.13	0.17	0.11	1.53	1.32	1.01
CD (5 %)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

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Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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