



RESEARCH ARTICLE

Effect of various treatments of organic and inorganic fertilisers on soil fertility and crop productivity

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Abstract

The present study aimed to assess soil fertility, yield attributes and seed quality parameters of *Sesamum indicum* L. by evaluating the impacts of inorganic fertiliser and vermicompost treatments. A pot experiment was executed utilising a completely randomised design (CRD) comprising five treatments and four replicates. The soil utilised for the experiment exhibited a sandy loam texture, a slightly alkaline pH of 8.5, negligible salinity with an electrical conductivity of 0.75 EC and low concentrations of available nitrogen at 75 kg ha⁻¹ and organic carbon at 0.22 %. The levels of phosphate, potash, sulfur and micronutrients were within normal ranges, specifically phosphate at 23 kg ha⁻¹, potash at 242 kg ha⁻¹, sulfur at 22.72 ppm, zinc at 1.02 ppm, iron at 4.88 ppm, copper at 0.24 ppm and manganese at 2.28 ppm. After the experiment, the growth parameters were significantly increased in response to the biofertilizer + vermicompost treatment followed by vermicompost alone. The yield attributes were observed highest in the vermicompost treatment but results are not significant ($p \geq 0.05$ level) whereas 100 seed weight was significantly improved by biofertilizer + vermicompost treatment (0.34 g). The seed quality parameters including total soluble sugars (5.16 mg g⁻¹) and protein content (192.69 mg g⁻¹) were significantly improved in the biofertilizer + vermicompost treatment and the total phenols was decreased in inorganic fertilizer treatments. A significant amount of oil (45.2 %) was reported in the vermicompost treatment. These results suggest that vermicompost + biofertilizer combination is best for sesame plant growth, seed weight and seed biochemical parameters [Total Soluble Sugars (TSS) and protein] whereas vermicompost application is beneficial for enhancing yield attributes and oil content as compared with chemical fertilizers. The current investigation is novel and concluded that the combination of vermicompost and biofertiliser was more beneficial for enhancing soil organic carbon and nitrogen levels as well as crop productivity and yield in semi-arid conditions of Rajasthan.

Keywords: biochemical; fertiliser; *Sesamum indicum*; soil; vermicompost

Introduction

The most significant oilseed crop in the Pedaliaceae family, sesame (*Sesamum indicum* L.), is cultivated in warm tropical and subtropical climates. With an average production of 27 % and a productivity of 441 kg ha⁻¹, India is the world's largest producer of sesame. With an average yield of 412 kg ha⁻¹, 12.59 million tonnes of sesame were produced in Rajasthan (1). Rajasthan's primarily sandy soils have low levels of organic matter and moisture, making them less fertile. Fertiliser must be applied to arid soils to boost sesame crop production and meet demand (2). Mineral fertilisers are widely used in agriculture to improve crop yields and soil fertility (3). In order to increase the yield of sesame crops, farmers in Rajasthan state also use chemical fertilisers like urea and diammonium phosphate (DAP). However, inorganic fertilisers are currently being criticised for their detrimental effects on the environment and human health in several ways (4).

However, chemical fertilisers are primarily used to increase crop yields; however, frequent fertiliser use reduces soil fertility and health, crop nutritional and grain quality and ultimately impacts human health and environmental sustainability (5-7). One of the main environmental issues facing the world today,

especially in developing countries, is the careless use of chemical fertilisers, which has resulted in pollution of the air, soil, food and water (8). Due to all the detrimental effects of synthetic fertilisers, farmers are now looking for more environmentally friendly and sustainable farming practices. In an effort to maintain and enhance soil quality and crop productivity, it is therefore time to switch from chemical fertilisers to less hazardous fertilisers based on organic materials that supply soil organic matter and helpful soil microorganisms (9). The use of organic fertilisers, such as farmyard manure, poultry manure and cattle dung, is becoming increasingly crucial for crop production and soil quality (10). Continuous use of organic fertilisers may increase carbon matter, water-holding capacity and reduce soil erosion and leaching processes because tropical and subtropical regions have very low carbon matter due to higher temperatures (11). Utilised in sustainable agriculture to enhance the plant nutrients found in soil, new biofertiliser techniques are non-toxic and eco-friendly (12). The application of nano-Silicon (nSi) was also found to improve *Vigna unguiculata* germination, shoot formation and root formation in a recent trend (13). Additionally, biochar promotes the conversion of N₂O to N₂ during denitrification by increasing the

stability and catalytic activity of N₂O reductase enzymes in denitrifying bacteria (14). A novel process activates char made from fermentation residues with calcium chloride to capture approximately 37.5 ± 4.7 kg of phosphorus per ton from the liquid fraction, producing a fertiliser that surpasses both raw residues and struvite in plant-available P and also enhances soil properties (15). The economics and market analysis suggest this recovered-P fertiliser could be cost-competitive with conventional options.

Farmers in Rajasthan favour crops that require less water and yield more because of the state's low soil fertility and lack of annual rainfall. Sesame is one such crop. The sesame crop was chosen for the current study due to its high drought tolerance and ability to be grown on a range of soil types, including sandy, salty and low-fertility soils (16). In previous studies, there is an unclear and comparative analysis of how chemical fertilisers and manures affect sesame growth in Rajasthan's sandy loam soil. In light of these considerations, the current experiments were designed to examine how inorganic, organic and biofertilisers affect the growth, yield characteristics and seed quality parameters of sesame plants grown in sandy loam soil.

Materials and Methods

Experiment site

The current investigation was conducted during 2017-2019 at Jaipur, Rajasthan (26°53'19.2" N 75°48'53.3" E). The crop was grown in the month of July and the maximum and minimum temperatures ranged between 28–35 °C to 20–30 °C, respectively (Fig. 1).

Soil sample and chemical analysis

The soil samples were collected from the Department of Botany, University of Rajasthan. 1 kg soil capacity plastic pots were used for the experiment. The texture of the soil was sandy loam and the chemical analysis was also done before growing the crop (Table 1). The physicochemical properties of soil, viz., pH, water holding capacity, electrical conductivity, organic carbon, total nitrogen, phosphate, potash, sulfur and micronutrients such as zinc, ferrous, copper and manganese were analysed as per the standard methodology (17).

Experiment design and treatment

For the experiment, plastic pots (13 cm in size) with 1 kg of soil were arranged in a complete randomised design with five treatments and four replicates. The treatments included two inorganic fertilisers: urea (46 % N) as N fertiliser denoted T₂ (20 kg N ha⁻¹RDF); DAP (18 %

N and 46 % P) as P fertiliser denoted T₃ (20 kg N + 25 kg P₂O₅ ha⁻¹ RDF), vermicompost as organic fertiliser denoted T₄ (10 t ha⁻¹ RDF) and *Azotobacter* (CFU 5 × 10⁷ cells g⁻¹) as biofertiliser denoted T₅ (5 kg in 500 kg organic manure/acre RDF). The doses used in this experiment were recommended by the Rajasthan Agriculture Research Institute (RARI), Durgapura, Jaipur. Plastic pots (13 cm in size) of 1 kg capacity were used for this experiment (Fig. 2) and five seeds were sown per plot and plants were thinned to one plant per plot after germination. 1 kg of soil was filled in each pot and a basal dose of potassium nitrate and soil enrichment manure was used before 15 days of the experiment. The sandy loam soil without any treatment serves as T₁ (control). For nitrogen fertilisation, urea was applied twice: the first dose at sowing time and again at 30 days after sowing. DAP as an NP fertiliser was applied in a single dose during sowing time. One dose of inorganic fertilisers was also applied till harvest time. Vermicompost was spread fifteen days before planting the crop. The chemical analysis of vermicompost is indicated in Table 2. The solid form of biofertiliser was combined with vermicompost and applied fifteen days before sowing. Additionally, the seed inoculation method was used. Pona A Bactor (nitrogen fixation) biofertiliser was used for the study.

The pots were irrigated thrice a week following the same watering schedules used in all the treatments. All the doses were applied according to the pot area and soil weight. These experiments were conducted in three successive rainy seasons. Harvesting was performed in October, when the colour of the sesame leaves changed from green to yellow. After the capsules were dried, they were cut and dried in the shade. Seeds were collected from the dried capsules for further morphological and biochemical studies. All the data were collected in three rainy seasons and the means of the pooled data were measured.

Plant material and measurements

Sesame (*S. indicum*) variety “super sona-51” is taken for the present research work, which is grown by Rajasthan farmers extensively.

Table 2. Chemical analysis of vermicompost

Chemical properties	Quantity
Organic carbon %	3.82
Nitrogen %	0.29
Phosphorous %	1.40
Potash %	0.72

*Vermicompost sample was analysed in Hydrel Laboratories (P) Limited, Ghaziabad.

Table 1. Physicochemical parameters of soil and their status regarding the Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India

Soil properties	Description and quantity	Status of experimental soil
Texture class	Sandy loam soil	-
Sand particles	72.28 %	-
Slit particles	18.07 %	-
Clay particles	9.63 %	-
pH	8.5	6.5-7.1 Moderately alkaline
Electrical conductivity	0.75 mS cm ⁻¹	0.2 Salt free
Organic carbon	0.22 %	0.5-0.75 Low
Nitrogen	75 kg ha ⁻¹	280-560 Very low
Phosphate	23 kg ha ⁻¹	10-24.6 Medium
Potash	242 kg ha ⁻¹	108-280 Medium
Zinc	1.02 ppm	0.4-1.2 Sufficient
Iron	4.88 ppm	2.5-4.5 Sufficient
Copper	0.24 ppm	≥ 0.20 Sufficient
Manganese	2.28 ppm	≥ 2.0 Sufficient

Ppm: Parts per millions, mS cm⁻¹: milliSiemens per centimeter.

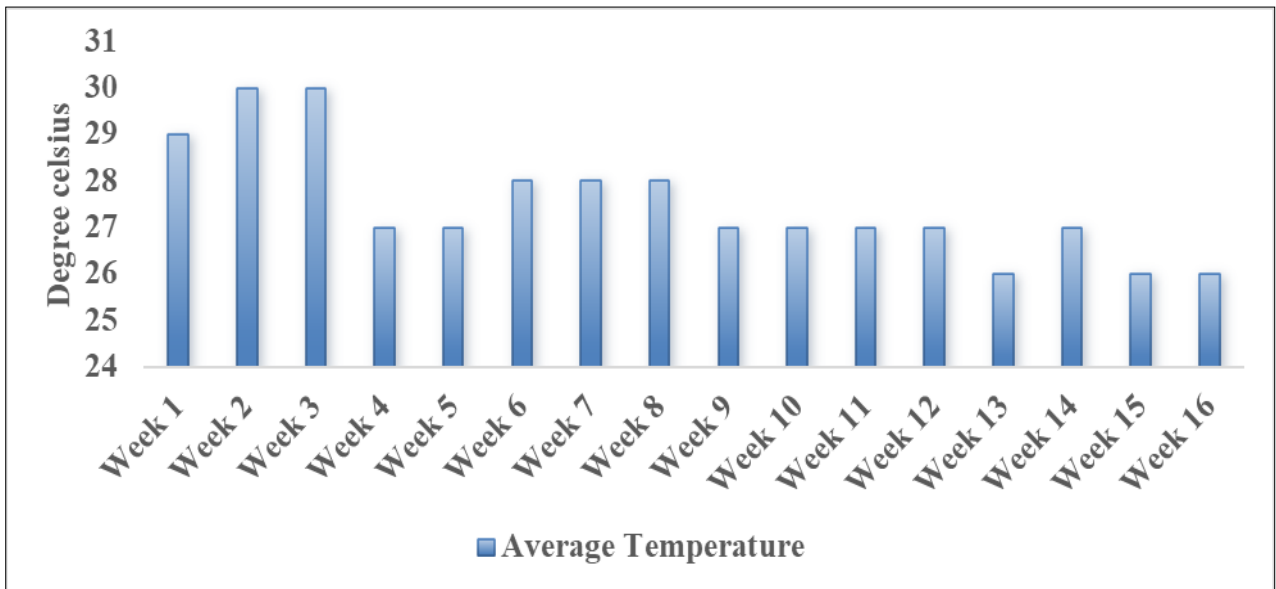


Fig. 1. Monthly average temperature during experiment (2017-2019).

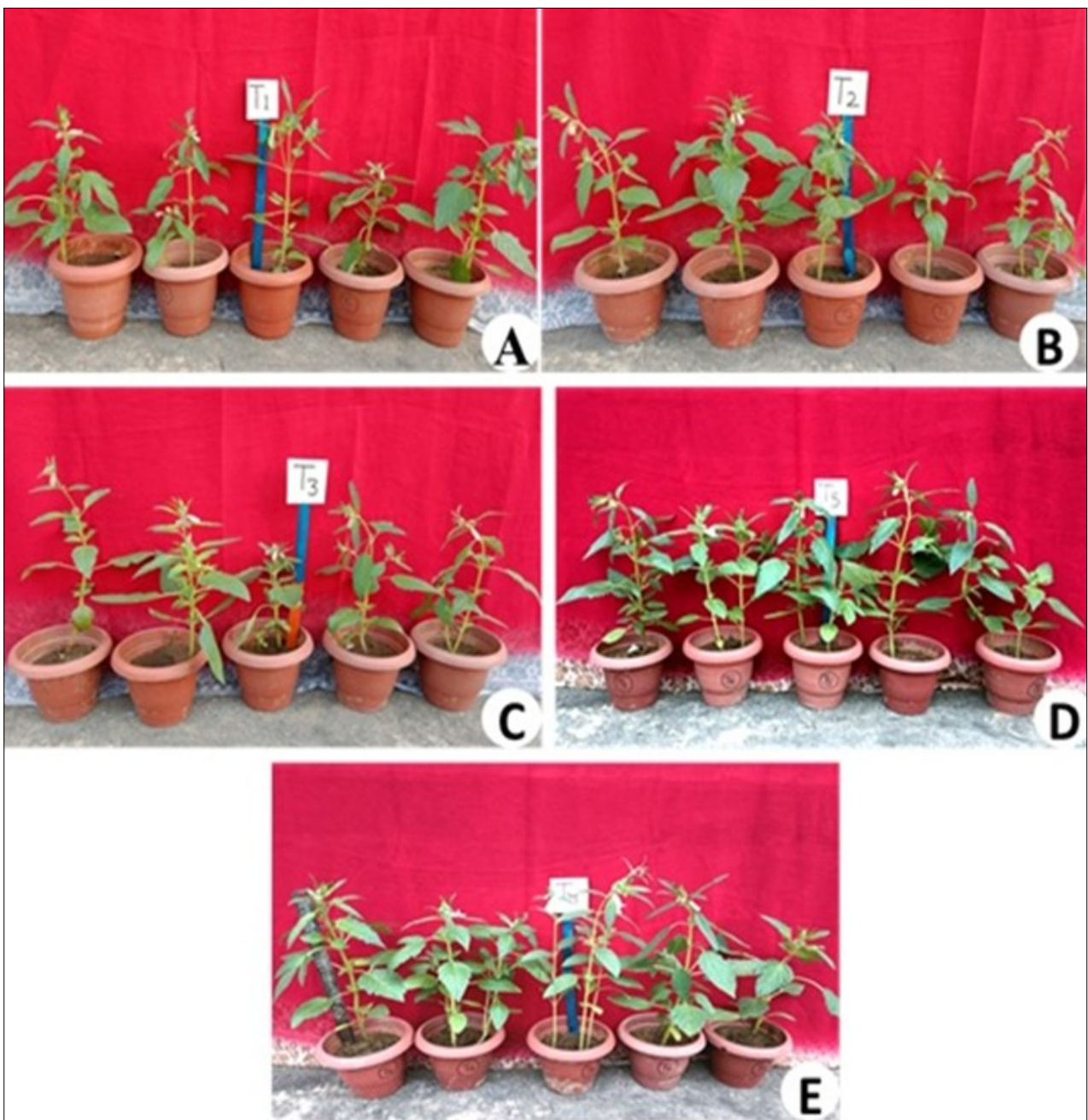


Fig. 2. Sesame plants grown in pots with different fertiliser treatments. T₁: Control (A), T₂: N fertiliser (B), T₃: NP fertiliser (C), T₄: Vermicompost (D), T₅: Vermicompost + Biofertiliser (E).

Seeds were commercially supplied by Shri Ram Agro Biotech, Gujarat. The following methods were used for measuring growth parameters, yield attributes and seed quality parameters:

Growth parameters

Growth characteristics such as shoot length, root length, total number of leaves per plant, number of nodes per plant, number of flowers per plant, inter-nodal length, petiole length, leaf length, leaf breadth and leaf area were estimated by taking 10 plants randomly from each treatment (pots) at the age of 6 weeks from planting.

Yield attributes

The number of capsules and the capsule weight were recorded when the plants reached the age of nine weeks. The number of seeds was calculated after the capsules matured. Seeds were collected from all capsules and the 100-seed weight was measured using a weighing scale (Model-Precisa XB 220A).

Seed biochemical quality parameters

The dried seeds were powdered finely and biochemical qualitative parameters such as total soluble sugars, starch, proteins, lipids, total phenols and oil content were estimated. Total soluble sugars (TSS) were extracted using the standard method on 50 mg of powdered sample in 80 % ethanol and concentrations were determined by spectrophotometer (Thermo Scientific Biomate 160 UV) (18, 19). For starch, a pellet was used, which was procured via the TSS extraction procedure and extracted via the standard method (20). The concentrations were subsequently estimated via the standard method (19).

Proteins were extracted from a 50 mg sample with 10 mL of 10 % TCA and further quantitative analysis was performed by the standard method (21). Total phenols were extracted by the method and quantitative estimation was performed by the standard method (22, 23). For lipid estimation, the standard method was used for extraction and quantification (24). Oil estimation was performed by using a Soxhlet apparatus and petroleum ether was used as the solvent for extraction (25).

Data analysis

The statistical analysis was done using the R language version 3.5 to compare the significance between different fertiliser treatments. For this, a one-way ANOVA was utilised and the "t" test was used to compare various variables across several treatments. The standard error mean (SEM \pm) and critical difference (CD) values between treatments were computed using OP Software.

Table 3. Effects of different treatments on growth characteristics (6 weeks of sowing) of the sesame crop

Treatments	Shoot length (cm)	Root length (cm)	Number of leaves/plant#	Number of nodes/plant#	Number of flowers/plant#	Inter-nodal length (cm)	Petiole length (cm)	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)
T ₁	26.26 \pm 7.76	18.88 \pm 3.32	8 \pm 2	5 \pm 0.54	2 \pm 0.89	4.62 \pm 0.81	1.56 \pm 0.37	5.8 \pm 0.33	314 \pm 0.42	11.53 \pm 1.89
T ₂	29.22 \pm 2.62	17 \pm 0.52	11 \pm 1.09*	6 \pm 0.44*	2 \pm 0.9	6.06 \pm 2.19	2.36 \pm 0.59	6.12 \pm 0.38	3.6 \pm 0.23	14.06 \pm 1.42*
T ₃	27.14 \pm 5.55	11.66 \pm 2.36*	10 \pm 0.89	5 \pm 0.55	2 \pm 1.41	5.52 \pm 0.81	2.12 \pm 0.67	6.12 \pm 0.35	3.24 \pm 0.77	13.16 \pm 2.56
T ₄	31.9 \pm 6.12	15.9 \pm 2.45	12 \pm 1.67*	7 \pm 0.54**	3 \pm 1.09	6.14 \pm 1.05	2.64 \pm 0.5	6.7 \pm 0.98	4.18 \pm 0.86*	18.57 \pm 3.8**
T ₅	37.62 \pm 5.23*	11.2 \pm 1.45*	12 \pm 1.68*	7 \pm 0.89**	4 \pm 0.44**	6.76 \pm 1.6	2.44 \pm 0.68	7.18 \pm 0.66**	4.44 \pm 0.41**	21.76 \pm 2.17***
CD ($p=0.05$)	7.58	4.1	2.02	0.81	1.32	NS	NS	0.79	0.78	3.33
SEM \pm	2.55	1.2	0.68	0.27	0.44	0.62	0.25	0.26	0.26	1.12

Level of significance: - Unmarked mean values are not significantly different at the 0.05 probability value. * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$ by ANOVA with complete randomised blocks; NS- Non-significant, T₁- Control, T₂- N fertiliser, T₃- NP fertiliser, T₄- Vermicompost, T₅- Vermicompost + Biofertiliser. # - Number of capsules, number of seeds values rounded up to a whole number

Results

Effect on physical and chemical properties of soil

pH, electrical conductivity, water-holding capacity, macronutrients (organic carbon, accessible nitrogen, phosphate and potash) and micronutrients (zinc, iron, copper, manganese and sulfur) were among the physical and chemical characteristics of the soil that were noted (Table 1). Soil samples were analysed before planting and it was discovered that the experimental soil had a sandy loam texture, a pH of 8.5, indicating a somewhat alkaline nature and an electrical conductivity of 0.75. The water-holding capacity was 36% (Table 1).

Growth characteristics

Table 3 summarises the following growth attributes: shoot length, root length, number of leaves, nodes, flowers, internodal length, petiole length, leaf length, leaf breadth and leaf area. When vermicompost and biofertiliser were applied together, the morphological and growth characteristics—such as shoot length, total number of leaves, number of nodes, number of flowers, internodal length, leaf length, leaf breadth and leaf area were significantly ($p \leq 0.05$) increased (Fig. 3-6). The highest shoot length (37.62 cm), number of leaves (12), number of nodes (7), number of flowers (4), inter-nodal length (6.76 cm), leaf length (7.18 cm), leaf breadth (4.44 cm) and leaf area (21.76 cm²) were recorded with biofertiliser + vermicompost treatment while minimum shoot length (26.26 cm), number of leaves (8), number of nodes (5), number of flowers (2), inter-nodal length (4.62 cm), leaf length (5.8 cm), leaf breadth (3.14 cm) and leaf area (11.53 cm²) were observed in control (Table 3). The root length was observed to be highest in control T₁ (18.88 cm), followed by T₂, T₄ and T₃ treatments and was found to be lowest in T₅ treatment (11.2 cm). Only the root length was significantly decreased due to fertiliser treatments. The highest number of leaves and nodes per plant was found similar in the T₄ and T₅ treatments (Fig. 4). In the ANOVA test, all the parameters were found significantly different ($p \leq 0.05$) except petiole length and inter-nodal length ($p \geq 0.05$) (Table 3).

Yield attributes

After the plants matured, some yield attributes such as the number of seeds per capsule, the number of capsules per plant and the weight of 100 seeds were recorded (Table 4). The maximum capsule weight (0.68 g), number of capsules per plant (10) and number of seeds per capsule (56) were recorded in vermicompost (T₄) treatment as compared to other treatments

Table 4. Effects of different fertilisers on the yield attributes of mature plants

Treatments	Capsule weight (g)	No. of capsules per plant #	No. of seeds per capsule #	100 seed weight (g)
T ₁	0.47 ± 0.22	6 ± 3.21	53 ± 1.15	0.28 ± 0.02
T ₂	0.41 ± 0.18	7 ± 2.3	55 ± 1.52	0.31 ± 0.02
T ₃	0.31 ± 0.13	9 ± 1.15	54 ± 2.08	0.30 ± 0.01
T ₄	0.68 ± 0.15	10 ± 2.64	56 ± 2	0.28 ± 0.01
T ₅	0.66 ± 0.25	7 ± 3.05	55 ± 0.57	0.34 ± 0.01**
SEm ±	0.112	1.49	0.90	0.009
CD ($p=0.05$)	NS	NS	NS	0.029

Level of significance: - Unmarked mean values are not significantly different at the 0.05 probability value. * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$ by ANOVA with complete randomised blocks; NS- Non-significant, T₁- Control, T₂- N fertiliser, T₃- NP fertiliser, T₄- Vermicompost, T₅- Vermicompost + Biofertiliser. # - Number of capsules, number of seeds values rounded up to a whole number

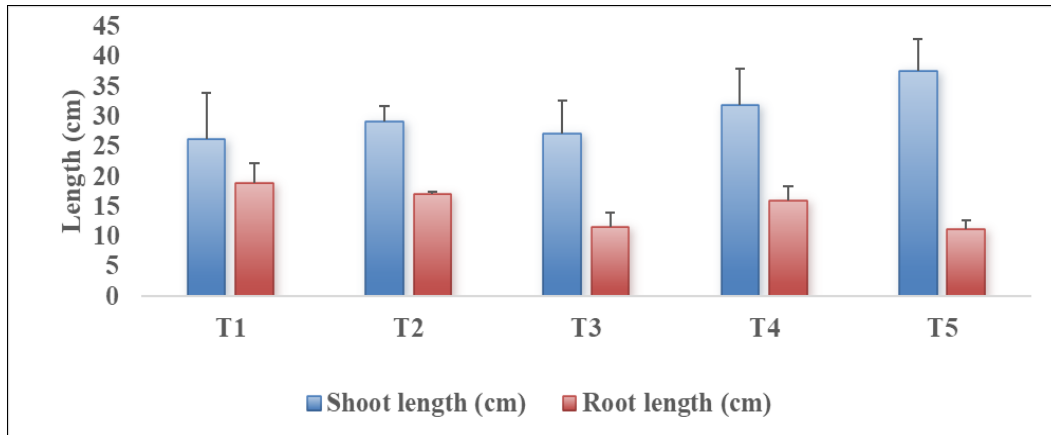


Fig. 3. Various treatments and their effect on the shoot and root length of sesame. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

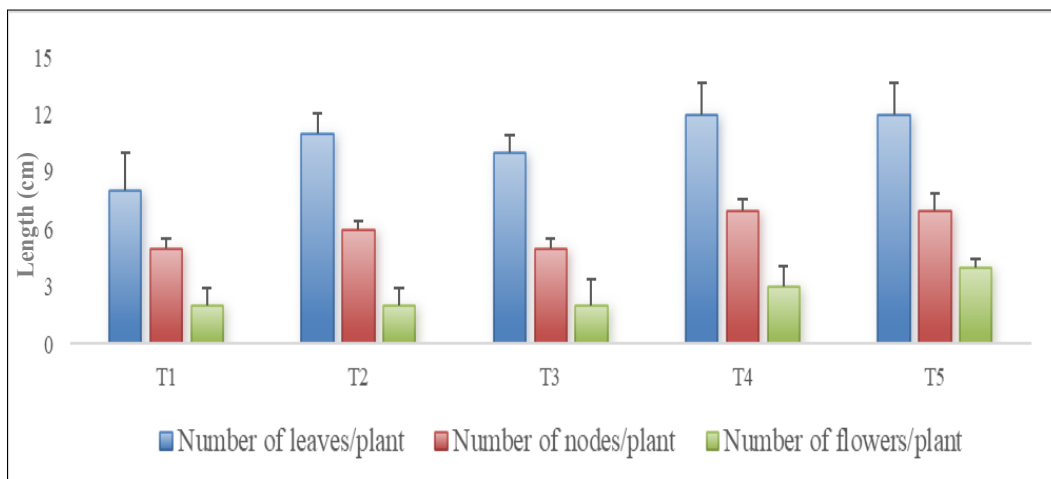


Fig. 4. Various treatments and their effect on leaves, nodes and flowers of the plant. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

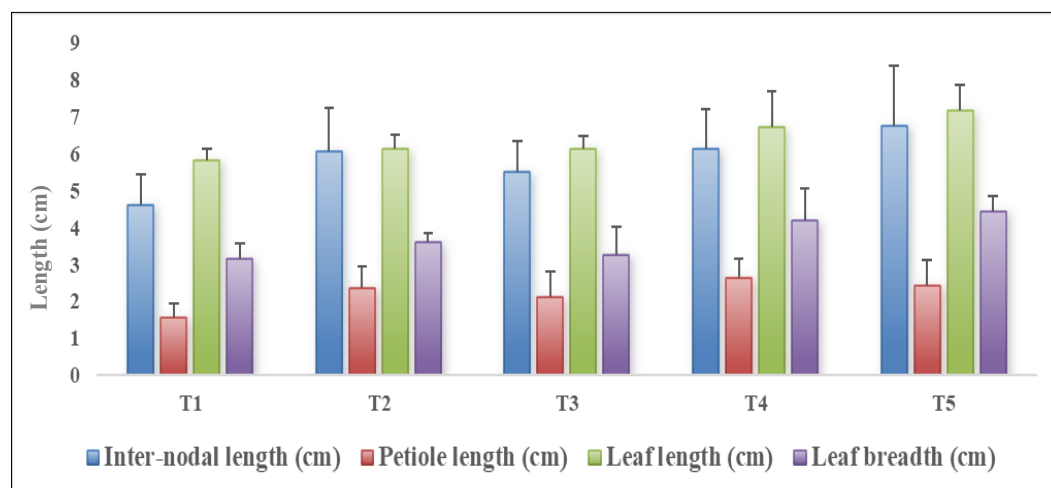


Fig. 5. Various treatments and their effect on Inter-node, petiole and leaf length. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

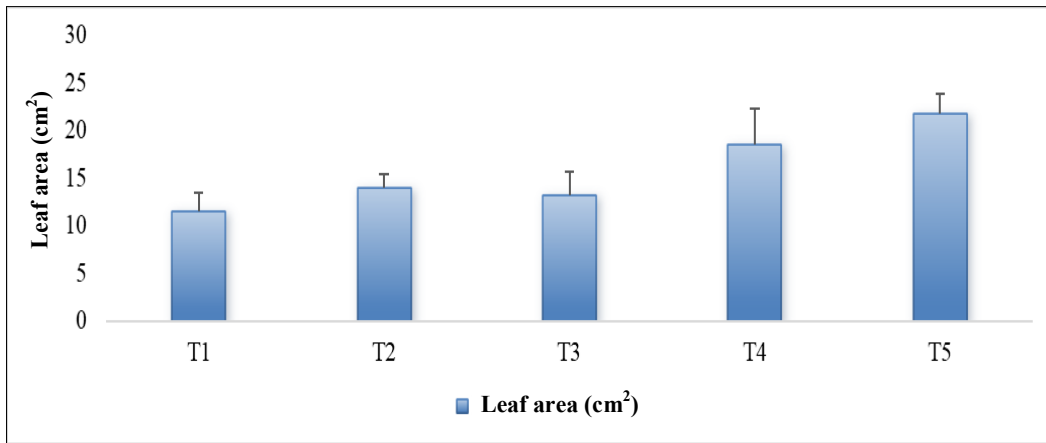


Fig. 6. Various treatments and their effect on leaf area. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

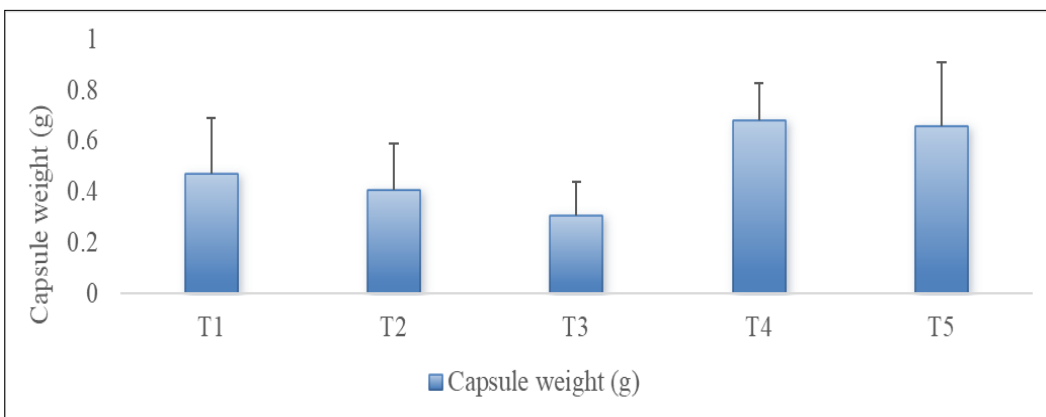


Fig. 7. Various treatments and their effect on capsule weight. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

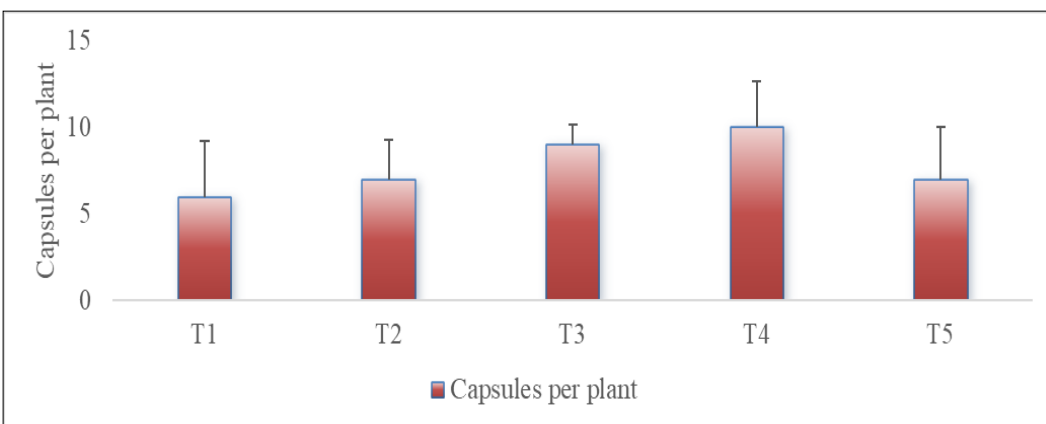


Fig. 8. Various treatments and their effect on capsule per plant. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

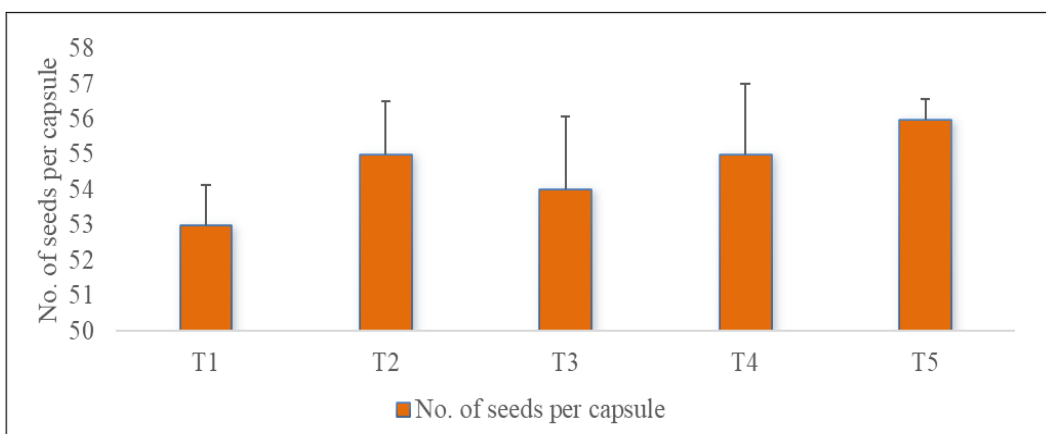


Fig. 9. Various treatments and their effect on the numbers of seeds per capsule. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

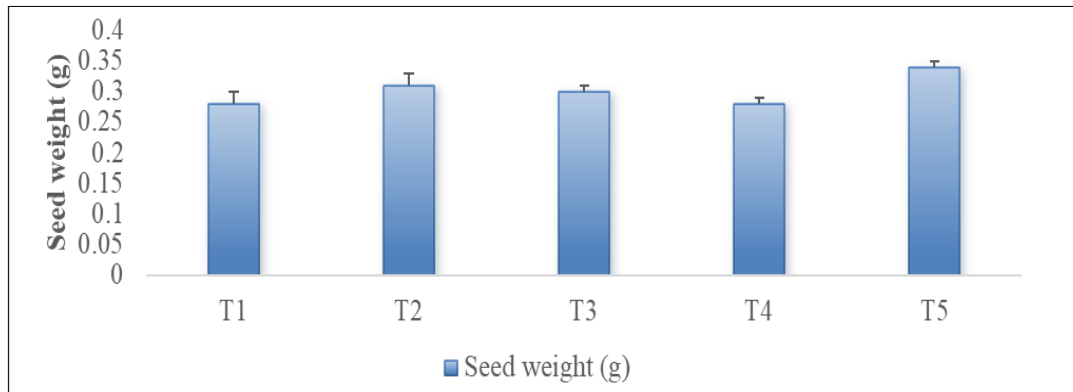


Fig. 10. Various treatments and their effect on seed weight. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

and found lowest in control (T₁), but these attributes did not significantly increase ($p \geq 0.05$) as indicated in Fig. 7-9. Only the 100 seed weight was significantly increased due to biofertilizer + vermicompost (T₅) treatment (Fig. 10).

Seed quality parameters

Sesame seeds biochemical quality parameters such as protein, carbohydrate, lipid and total phenol are illustrated in Table 5. The TSS were found to be highest in the T₅ treatment (5.16 mg g⁻¹) and the lowest amount was found in the T₂ treatment (4.13 mg g⁻¹). TSS was significantly affected by the T₅ treatment ($p \leq 0.05$) than other treatments and the control. However, the starch content was highest in the T₁ (control) (9.2 mg g⁻¹) and lowest in the T₂ treatment (4.73 mg g⁻¹). Starch content was significantly reduced in all other fertiliser treatments. The protein content of the sesame seeds was found to be maximum in the T₅ treatment (192.69 ± 7.69 mg g⁻¹),

followed by the T₄ treatment (183.25 mg g⁻¹) and the minimum value was found in the T₁ (control) (117.16 mg g⁻¹), as indicated in Table 5. Protein content was significantly increased ($p \leq 0.05$) due to all treatments except the T₃ (NP fertiliser) treatment.

The lipid content was found to be highest in T₃ treatment (48.1 mg g⁻¹) and lowest in T₁ (46.4 mg g⁻¹). Compared with the other treatments and the control, the lipid content of sesame seeds was only significantly affected ($p \leq 0.05$) by the T₃ treatment. The total phenol content was greatest in the T₅ treatment (2.14 mg g⁻¹), but it was not significant at the 0.05 probability level. In the T₂ and T₃ treatments (1.47 and 1.44 mg g⁻¹), total phenolic content significantly decreased (Table 5). The oil content in sesame seeds was found to be 31 % in T₁, 33.8 % in T₂, 44.8 % in T₃, 45.2 % in T₄ and 38 % in T₅ treatment. It was significantly affected ($p \leq 0.05$) by T₄ treatment followed by T₃, then T₅ treatment and least in control (T₁) (Fig. 11).

Table 5. Seed quality parameters after being treated with different fertilisers

Treatments	Total soluble sugars (mg g ⁻¹)	Starch (mg g ⁻¹)	Protein (mg g ⁻¹)	Lipid (mg g ⁻¹)	Total phenols (mg g ⁻¹)
T ₁	4.56 ± 0.20	9.2 ± 0.2	117.16 ± 19.29 ±	46.4 ± 0.36	2.1 ± 0.05
T ₂	4.13 ± 0.21	4.73 ± 0.30***	174.81 ± 1.34**	46.4 ± 0.4	1.47 ± 0.04***
T ₃	4.27 ± 0.09	5.87 ± 0.11***	128.28 ± 21.65	48.1 ± 0.9*	1.44 ± 0.10***
T ₄	4.24 ± 0.13	7.4 ± 0.2**	183.25 ± 5.77**	46.5 ± 0.4	2.01 ± 0.07
T ₅	5.16 ± 0.05*	7.82 ± 0.02**	192.69 ± 7.69**	46.6 ± 0.15	2.14 ± 0.06
SEm ±	0.08	0.11	7.89	0.31	0.04
CD (0.05)	0.28	0.35	25.21	0.99	0.12

Level of significance:- Unmarked mean values are not significantly different at the 0.05 probability value. * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$ by ANOVA with complete randomized blocks; NS - Non-significant, T₁- Control, T₂- N fertiliser, T₃- NP fertiliser, T₄- Vermicompost, T₅- Vermicompost + Biofertiliser.

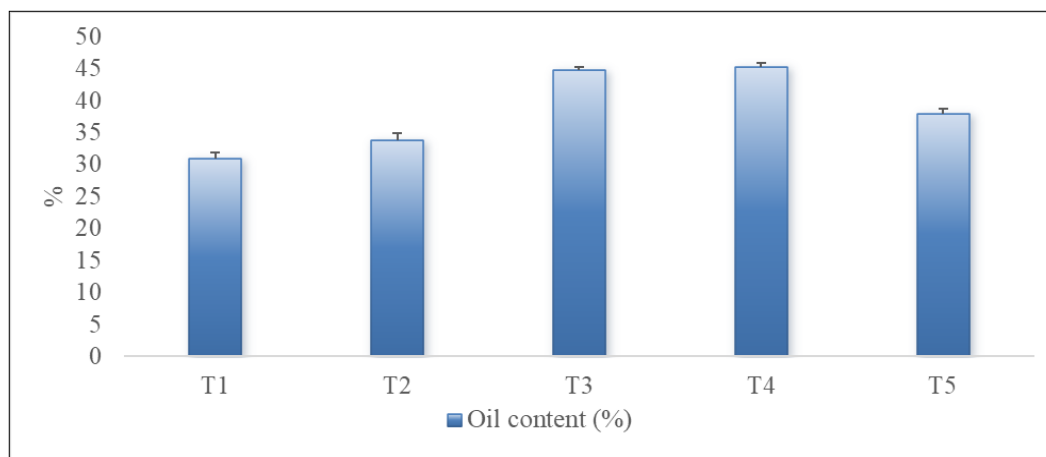


Fig. 11. Effects of fertilisers on oil content of seeds. T₁: Control, T₂: N fertiliser, T₃: NP fertiliser, T₄: Vermicompost, T₅: Vermicompost + Biofertiliser. The standard deviations (SD ±) are shown by the error bars.

Discussion

Growth characteristics

The results of our study highlight on positive impact of the combined application of biofertilizer + vermicompost and vermicompost alone on sesame growth characteristics. The increase in growth characteristics due to biofertiliser + vermicompost treatment might be due to biofertilisers containing microorganisms that enhance plant growth by providing nutrient supply to the host plant when applied to seeds, plants or soil (26). They are also utilised to promote microbial activity, which makes nutrients more readily available for plants to absorb (27, 28). Researchers found that biofertiliser and organic fertiliser mix, along with reduced doses of inorganic fertilisers, crop morphological characteristics and yield attributes were induced as compared to inorganic fertilisers at full doses (29, 30). Similarly, research has demonstrated that biofertiliser application with vermicompost and half-dose of chemical fertilisers produces the highest growth characteristics (31). So, their study indicated that chemical fertiliser may be replaced by bio-organic fertilisers to overcome environmental pollution.

Vermicompost had a significant impact on growth characteristics as compared to inorganic fertilisers. The current study also showed that vermicompost by itself considerably enhanced growth characteristics, followed by the combined application of biofertiliser and vermicompost. The impact could be because of the presence of microorganisms in vermicompost, resulting in a high level of microbial activity that can produce growth regulators such as auxins, gibberellins and cytokinins that may be beneficial for plant growth and development (32).

A current study documented that, through molecular interactions with denitrifying bacteria, biochar lowers N₂O emissions, mainly by stabilising N₂O reductase enzymes and promoting N₂O conversion to N₂ (14). In addition to reducing enzyme fluctuations through hydrophobic and hydrophilic interactions, biochar also adsorbs N₂O and directs it to the enzyme's active site. Knowing these relationships can aid in the development of more sustainable and cost-effective fertilisers based on biochar that release nutrients more gradually and are better for the environment. In another investigation, production of algal biochar in Central Europe costs over €110 kg⁻¹, far exceeding typical biochar market prices. To improve feasibility, algae should be used for higher-value products, with biochar production serving as the final refining step (15).

In the present study, root length was significantly decreased due to fertiliser treatment, but, on the contrary, many scientists reported root length increase in response to fertiliser treatment (33, 34). The reason behind our results may be that due to fertiliser and manure treatment, nutrients become easily available at the upper surface of the soil and sesame plants absorb them from their roots. Thus, comparatively shorter roots are observed as compared to the control. Another study reported that in soil, water and nitrogen are movable. Compared with other nutrients, these nutrients are less dependent on dense root systems for successful uptake, since they may migrate to deeper soil layers and reach the roots more readily than other soil nutrients (35). Therefore, roots become shorter and less dense in response to fertiliser and manure treatments. They also reported that rooting depth seems to be more confined to sandy soils and that deeper soil layers contain smaller amounts of nitrogen and

water; thus, deeper roots in sandy soils are less valuable.

Yield attributes

The yield attributes were found to be maximum in vermicompost treatment followed by biofertiliser treatment, but the results are not significant. The reason may be related to the experimental soil, which was sandy loam in texture and contained low organic carbon and nitrogen (Table 1). However, primarily growth characteristics were significantly improved by the fertilisers and manures application significantly, but yield attributes did not improve significantly. In previous studies, it was considered that sesame is a heavy feeder crop, consuming the most nitrogen out of all nutrients (36). The environmental conditions, such as high temperature and transpiration, may be attributed to the low water retention capacity and thus nutrients are not available to plants till the harvesting time. The high permeability of sandy soils to water and associated nutrients limits crop productivity (37). The RDF of vermicompost increased the yield attributes.

The 100 seed weight was significantly increased in biofertilizer + vermicompost treatment than in other treatments. Research has demonstrated that the 1000 seed weight of *Anethum graveolens* L. plants was also influenced by biofertiliser treatment (38). This may be correlated with improved physicochemical properties of soil, resulting in increased amounts of chlorophyll a, chlorophyll b, proteins and lipids by applying vermicompost and biofertiliser to plants. Research indicates that increased and prolonged availability of nutrients, improvement in physical and biological activities of soil, such as the use of vermicompost, results in enhanced plant growth and yield attributes (39).

It may be said that vermicompost has a better nutritional content than conventional compost due to the valuable contribution of earthworms to raising the mineralisation rate and humification. This makes vermicompost excellent organic manure for enhancing the development, production and quality of different plants (40). Research has found that the vermicompost combined with *Azotobacter* biofertiliser as seed inoculation was the most effective treatment for enhancing yield parameters as opposed to other treatments (41). Our results are in harmony with previous reports. This may be due to bacterial phytohormones as Indole-3-acetic acid (IAA), which was raised in inoculated plants than in controls and resulting in an increase in other yield attributes (42).

Seed quality parameters

Sesame seeds are a rich source of fibre, secondary metabolites such as lignans, saponins, flavonoids and phenolic compounds and a significant amount of oil (50–52 %), proteins (19–25 %), carbohydrates (16–18 %) and vital minerals (43). The amount of oil and protein in sesame has a significant impact on the market price for farmers (44). Considering all these factors, seed quality parameters such as TSS, starch, protein, phenols, lipids and oil content were measured as affected by different fertilisers. TSS were significantly affected by the biofertiliser treatment ($p \leq 0.05$) as compared to the other treatments and similar outcomes have been reported with an increased amount of TSS, sugars and ascorbic acid content in tomato fruits (44). Similar results were also recorded in rice plants (45). Research has demonstrated that starch and soluble sugars can be stored with a low nitrogen supply. This is a sign of nutritional stress caused by low N levels.

In the current investigation, protein content was reported

to increase in biofertiliser treatment followed by vermicompost, than inorganic fertiliser and control. Similar findings were documented in a previous study, where the supply of nitrogen contributes to the protein content, amino acid content, protoplasm and chlorophyll formation (27, 46). Phenolic compounds were reported to be highest in biofertiliser treatment, but the results are not significant, whereas chemical fertilisers significantly reduced the phenolic compounds. Previous studies on rapeseed revealed that no clear fertilisation effects on phenolic compounds were seen (47). However, research indicates that a significant decrease in phenolic compounds in mustard leaves was caused by increasing the level of N fertilisation (48). Phenolic compounds were the highest reported in biofertiliser + vermicompost treatment. A report of a pot experiment also showed the highest level of phenolic compounds accumulated in the leaves while treated with cycocel and biofertiliser (49). The utilisation of accumulated nitrate in plants, which allows them to use more carbohydrates for structural growth under the effect of biofertiliser application, might be the cause of the higher phenol content in the leaves of biofertiliser treated plots (50). Compared with those in the other treatments, the oil content was significantly increased in the vermicompost treatment, followed by the NP treatment and lowest in the control. Similarly, research indicates that compared with nitrogen and phosphorus fertilisers, vermicompost treatment increased the amount of seed oil in groundnuts (51). This may be caused by the gradual availability of nitrogen and other nutrients in vermicompost. Furthermore, organic fertilisers improve the physical qualities of soil, which promote plant development, photosynthesis and eventually oil synthesis (52, 53).

Conclusion

The study concludes that the combined application of vermicompost and biofertiliser significantly enhanced soil fertility, nutrient availability and yield performance of *S. indicum* under semi-arid conditions of Rajasthan. This integrated treatment improved soil organic carbon, nitrogen and micronutrient content more effectively than inorganic fertilisers or vermicompost alone. The results highlight that vermicompost and biofertiliser together not only promote sustainable soil health and crop productivity but also offer an eco-friendly alternative to chemical fertilisers for sesame cultivation in nutrient-deficient soils.

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Authors' contributions

KK carried out the experiment, sample collection and analysis. SPC reviewed and revised the manuscript. A did the Data analysis. MRH worked on a field experiment and helped in sample collections. MS laid out the design of the experiment. 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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