Agriculture Association of Textile Chemical and Critical Reviews Journal (2023) 253-260

AATCC Review

08 November 2022: Received
13 March 2023: Revised
21 May 2023: Accepted
25 June 2023: Available Online

www.aatcc.peerjournals.net

Research Article

Open Access

Efficacy of Integrated Nutrient Management on Growth and Yield of Indian Mustard (*Brassica juncea* L.): An Experimental Study

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ABSTRACT

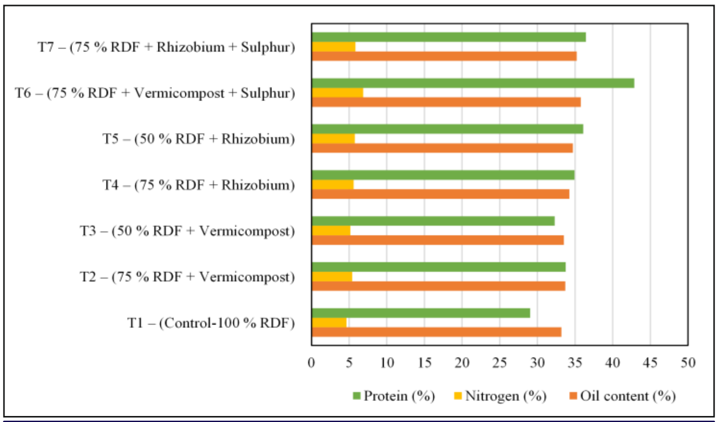
This research aimed to assess the efficacy of integrated nutrient management (INM) on the growth and yield of Indian mustard (Brassica juncea L.). The experiment comprised seven treatments, namely control as 100% recommended dose of fertilizer (RDF): T1; 75% RDF + vermicompost: T2; 50% RDF + vermicompost: T3; 75% RDF + Rhizobium: T4; 50% RDF + Rhizobium: T5; 75% RDF + vermicompost + sulfur: T6; and 50% RDF + Rhizobium + Sulfur: T7, respectively. The experiment was designed in a Randomized Block Design with three replications, and various observations were made on plant growth, the number of primary and secondary branches, yield, and quality parameters. The results of the experiment indicated that the T6 treatment demonstrated the most favorable outcomes in terms of plant height (197.54 cm) at the harvest, number of primary and secondary branches (9.3 and 12.3), and other growth parameters compared to the control treatment. Concerning yield parameters, the same treatment exhibited the highest siliqua length (6.76 cm), test weight (6.26 g), and seed yield (1690 kg/ha), while the lowest yield parameters were observed in the Control treatment (100% recommended dose of fertilizer). Additionally, the T6 treatment recorded the highest oil content (35.76%) and protein content (42.87%), whereas the Control treatment had the lowest quality parameters. Based on the findings of this study, it can be concluded that the T6 treatment showed the most effectiveness in enhancing the growth, yield, and quality attributes of Indian mustard.

Keywords: *fertilizer reduction; oil crops; nutrient management; sustainable agriculture*

Statement of Sustainability

This study provides valuable insight into sustainable agricultural practices by investigating the effectiveness of INM practices. INM's potential for optimizing nutrient use, reducing chemical use, and increasing crop productivity is consistent with sustainable farming objectives. The findings will highlight environmentally friendly and economically viable approaches to mustard production, ensuring long-term environmental preservation and improved food security. For a resilient and resource-efficient future, this research highlights the importance of adopting sustainable agricultural strategies.

Graphical abstract:



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DOI: https://doi.org/10.58321/AATCCReview.2023.11.03.253

INTRODUCTION

After cereals, oilseeds rank as India's second most important agricultural commodity, holding unique significance in the current era of energy scarcity. They play a crucial role in addressing human and animal malnutrition [1]. To maximize their potential yield, there is ample opportunity for oilseeds to increase both acreage and production. The productivity of oilseed crops heavily relies on factors such as selecting high-yielding disease and pest-resistant varieties, implementing efficient crop rotation, timely planting, achieving adequate plant stands, providing balanced nutrition, employing proper plant protection, irrigation, and timely weed control [2, 3].
Among the major oilseed crops, Indian mustard (Brassica juncea L.) stands out as a perennial annual herb belonging to the Brassicaceae family. Indian mustard is an amphidiploid plant with 36 chromosomes (2n). It has a long history of use, dating back to ancient times, and is even referenced as one of the greatest herbs in the Bible [4]. Indian mustard is known by various names, with "Rai" and "Laha" being common ones. The crop thrives under diverse agro-climatic conditions, making it a versatile member of the Brassica family. Indian mustard can be

cultivated in both irrigated and rainfed conditions, and it adapts well to sandy as well as heavy soils. The seeds and oil of Indian mustard find widespread use in cooking, as well as in the production of hair oils and medicinal products for humans [5, 28]. Additionally, the oil cake derived from the crop serves dual purposes as both a feed for livestock and a fertilizer for crops. Furthermore, the stem and leaves can be utilized as green feed for cattle [6].

India is one of the largest oilseeds-producing countries in the World. Mustard, soybean, groundnut, sunflower, sesame, and safflower are among the major oilseed crops grown in the country [7]. With an increase in India's population, per capita consumption of oils and fats is steadily increasing. India is a major producer of oilseeds. However, it also imports a significant amount of edible oil to meet its domestic needs. To supplement its domestic production, the country imports oils such as palm oil, soybean oil, sunflower oil, and others [8]. Overall, the development of oilseed crops in India is closely linked to the growth of the country's population, changes in dietary habits, agricultural policies, and external factors such as global oil prices and trade dynamics.

Nutrient management stands out as one of the most essential agronomic methods for enhancing crop output. In high-input production systems, Integrated Nutrient Management (INM) plays a vital role in preserving soil health and increasing fertilizer usage efficiency, ensuring high crop yield [9, 29]. Neither relying solely on chemical nor organic fertilizers can sustain soil fertility and crop production. Therefore, a safe combination of organic manures, fertilizers, and biofertilizers is necessary, as complete reliance on either organic or chemical farming is not viable. The primary objective of INM is to minimize the usage of chemical fertilizers by optimizing the balance between fertilizer inputs and crop nutrient requirements, thereby improving yields and profitability, and reducing pollution [10]. A well-balanced and effective combination of organic and inorganic fertilizer sources can boost the crop's yield potential [11].

Mustard, being a high-potential crop, can benefit from a well-planned set of practices, with INM playing a key role in ensuring sustainable agriculture and agricultural production [12]. Implementing INM can help reduce the chemical burden that contributes to soil and plant health issues. Maintaining a sufficient level of soil organic matter is crucial to safeguard soil structure, biomass, and overall productivity [13]. Soil organic matter significantly influences the dynamics of soil nutrients by temporarily storing nutrients through various biochemical processes, thus acting as a nutrient sink. The organic nutrients stored in the soil are essential for ensuring nutrient availability to plants. Maintaining an appropriate level of soil organic matter is considered a guiding principle while devising suitable soil management strategies [14]. Thus, a decline in soil organic matter content is likely to be indicative of reduced soil productivity.

Considering the above facts, an experiment was conducted at Dev Bhoomi Uttarakhand University, Dehradun during the Rabi Season of 2022-2023 to assess the efficacy of integrated nutrient management on the growth and yield of Indian mustard (*Brassica juncea* L.).

MATERIALS AND METHOD

2.1 Experimental Site

The research farm of Dev Bhoomi Uttarakhand University is located in Dehradun, situated between 78° 04' E longitude and 30° 13' N latitude. It lies at an elevation of 435 meters above mean sea level (MSL) and is situated in the lesser Himalayan region.

2.2 Soil Characteristics

To assess the physical and chemical properties of the soil, samples were collected from various locations within the field at a depth of 0-15 cm, using a soil auger, before experimenting. These samples were then mixed and analyzed to estimate different physical and chemical characteristics. The results of this analysis are presented in Table 1. Based on the examinations, the soil at the location exhibited a sandy loam texture, a neutral pH, and a slightly saline reaction. Furthermore, the soil showed a high concentration of organic carbon, medium levels of nitrogen and phosphorus, and a low level of potassium in terms of nutrient availability.

Table 1. Physical-chemical properties of soil sample at the experimental field

Parameter	Value	Method Used
Fine sand (%)	53.40	Hydrometer method
Silt (%)	25.40	Hydrometer method
Clay (%)	21.30	Hydrometer method
Textural class	Sandy clay loam	Triangular Diagram
Soil pH	7.2	pH meter using a glass electrode
Electrical conductivity (dS/m)	0.33	EC meter using conductivity method
Organic carbon (%)	1.31	Wet chromic acid digestion
Available Nitrogen (kg/ha)	301.5	Alkaline permanganate method
Available Phosphorus (kg/ha)	12.14	Olsen's method
Available Potassium (kg/ha)	233.6	Ammonium Acetate extract using flame photometer

2.3. Climate and Weather Conditions

Dehradun is situated between the latitudes 29° 58' and 31° 2' north and the longitudes 77° 37' and 78° 18' east. The region experiences a humid subtropical climate, with summer daytime temperatures ranging from 30°C to 43°C, and winter daytime temperatures varying from 5°C to 25°C. The overall climate of the Dehradun region can be classified as humid subtropical on an annual basis. The summers (March to June) are characterized by hot and dry conditions, while the winters (December to February) are frigid. The monsoon season (June to September) brings wet and humid weather, with dependable rainfall. The annual rainfall in the area amounts to 964 mm.

2.4. Experimental Design

The experiment was conducted at the agricultural research fields of Dev Bhoomi Uttarakhand University, located in Dehradun.

Mustard (Brassica juncea L.) was chosen as the target crop for the study. A total of seven different fertilizer treatments were applied, with each treatment replicated three times, resulting in 21 plots in total. Each plot measured 9 meters in width and covered an area of 14 square meters (9 × 14 m^2). The gross plot size was 3.0 meters in width, covering an area of 2.0 square meters (3.0 × 2.0 m^2). To minimize biases and ensure accurate observations, a Randomized Block Design (RBD) was employed in the study. The mustard crop was sown during the Rabi season, typically falling between late October and early November. The essential nutrients Nitrogen (N), Phosphorus (P), and Potassium (K) were provided through Urea, Diammonium Phosphate (DAP), and Muriate of Potash (MOP), respectively. The recommended fertilizer dose was 36:36:24 NPK (Nitrogen:Phosphorus:Potassium) per hectare. Mustard seeds were sown at a rate of 5 kg/ha. The experimental design layout is presented in Table 2, and the recommended doses of fertilizers (RDF) were applied as a base application for each treatment. Specifically, before sowing, 60 kg/ha of nitrogen was uniformly applied using urea, 30 kg/ha of potassium was applied with muriate of potash, and 60 kg/ha of P2O5 was applied with DAP. Vermicompost was applied to plots T2, T3, and T6, while Rhizobium was applied to plots T4, T5, and T7, and Sulfur was applied to plots T6 and T7.

Table 2. Details of treatments.

Treatment	Configuration
T1	Control (100% RDF)
T2	75 % RDF + Vermicompost
T3	50 % RDF + Vermicompost
T4	75 % RDF + Rhizobium
T5	50 % RDF + Rhizobium
T6	75 % RDF + Vermicompost + Sulfur
T7	75 % RDF + Rhizobium + Sulfur

2.5. Field Operation and Crop Cultivation Practice

Using a tractor-drawn moldboard plow, the field was prepared after harvesting the previous crop. The remaining roots were manually removed to ensure better field preparation. The main field was then subjected to 3-4 plowings using a tractor-drawn cultivator, followed by harrowing, digging, and leveling to achieve a favorable soil structure. The 3 × 2 m beds, paths, and channels were arranged as per the designated layout. Pre-sowing irrigation was applied to the field. To maintain a consistent plant population in each plot, gap filling was carried out early on to replace failed or dead seedlings. About 15-20 days after sowing (DAS), the dense plant population was manually thinned to 30 × 10 cm spacing, ensuring a uniform plant population after the complete germination of the plot. Hand weeding was performed as needed to keep the plots weed-free. A total of three wedding sessions were conducted during the experimentation period. The crop received irrigation immediately after planting, at 30 DAS, during the flowering stage, and at 60 DAS. Pre-sowing irrigation was also applied to ensure sufficient moisture for the plants. As there were no incidents of diseases or pest attacks, no plant protection measures were implemented. Harvesting was done using a sickle once most of the crop plants had reached maturity. The harvested plants were left to dry in the plots for a week. After drying, the produce from each net plot was tied into bundles and weighed before being threshed by pounding the plants with a stick. The seed yield was measured by weighing the seeds separated from the threshed chaff. By deducting the seed yield from the biological yield, the straw yield was calculated.

2.6. Data Collection

The height of the five tagged plants was measured in centimeters from the ground to the plant's tip at 30, 60, and 90 DAS, and harvest. Subsequently, the average height was calculated. The main branches were those that originated from the main stalk, and their number was recorded per plant basis for each of the five tagged plants in every plot. Secondary branches are the ones that grow from primary branches, and their count per plant was also recorded. At 30, 60, and 90 DAS, and harvest, five tagged plants were randomly selected for assessment. The plant samples were first dried in the shade and then further dried at 60°C in a hot air oven until a constant weight was achieved. For each of the five tagged plants, the siliqua length was measured, and the mean value was calculated. The weight of all siliqua in the five tagged plants was measured and expressed per plant. To determine the number of seeds per siliqua, a thorough mixing of all siliqua from the five tagged plants was done, and a random selection of a few siliqua was counted for seed quantification. The average number of seeds per siliqua was determined based on the total count. The seed yield per plant was calculated by threshing the siliqua of the five tagged plants from each plot and recording the seed weight in grams before calculating the average. The total quantity of seeds per plant for each plot was counted, and the mean value was calculated. Additionally, 1000 seeds were collected from each plot during harvest, and their weight in grams was noted. After threshing, the weight of the seed per plot area was recorded in kilograms (kg) per plot. The biological yield was calculated by summing the seed yield and stover yield (recorded and averaged) for each plot:

Biological yield = Seed yield + Stover yield

2.7. Determination of Quality Parameters

The harvest index (in percentage) was computed by dividing the seed yield by the biological yield and then multiplying the result by 100 [15].

Harvest Index (%) = (Seed Yield / Biological Yield) × 100

To determine the oil content of mustard seeds, Soxhlet's Ether Extraction Method was employed. The oil yield (in kg/ha) was calculated using the following formula [16]

Oil Yield (kg/ha) = (Oil Content (%) × Seed Yield (kg/ha)) / 100

The nitrogen content in the seeds was assessed by crushing dry seed samples and digesting them with sulfuric acid and hydrogen peroxide. The nitrogen concentration was measured using Nessler's reagent through a colorimetric method. The protein content in the seeds was obtained by multiplying the nitrogen percentage by 6.25, following the AOAC (2009) standard methods.

2.8. Statistical Analysis

The observations underwent statistical analysis using the Randomized Block Design (RBD). Mean differences were tested using the F-test at a 5% level of significance (LOS). The Critical Difference (CD) at a 5% level of probability was employed for comparing the treatments.

3. Results and Discussion

3.1. Effect of INM on Plant Height of Indian Mustard

The data on plant height revealed a gradual increase in height as the crop grew, irrespective of the treatments (Table 3). INM had a minor influence on plant height at different growth stages, namely 30, 60, and 90 DAS, and at harvest. At 30 DAS, the maximum plant height of mustard was observed as 58.36 cm with the application of T6, while the minimum plant height of 39.73 cm was found in the control (T1) group. At 60 DAS, the maximum plant height of mustard was 127.99 cm with the application of T6, whereas the minimum plant height of 78.64 cm was recorded in the control (T1) group. Similarly, at 90 DAS, T6 exhibited the highest plant height of 172.24 cm, and the lowest height of 141.33 cm was observed in the control (T1) group. At harvest, the highest plant height of 197.54 cm was noted in the T6 group, while the least height of 153.85 cm was recorded in the control (T1) group. Sulfur, which regulates chlorophyll production and enhances growth properties, might be responsible for the increase in plant height. Additionally, the availability of nutrients throughout the crop growth cycle may have contributed to the overall plant height increase. The effects of different NPK and sulfur levels on plant height were found to be significant at 30, 60, and 90 DAS, and harvest. These results were consistent with those reported by Devi et al. [17] where the use of 30 kg/ha of sulfur significantly improved the plant height of Soybean (Glycine max) compared to the control, and Akter et al. [18] found that plant height significantly increased with increasing P and S levels up to 30 and 20 kg and 30 kg/ha of sulfur.

Table 3. Efficacy of Plant height (cm) during successive stages of mustard as influenced by INM.

Treatments	Plant Height (cm)			
	30 DAS	60 DAS	90 DAS	Harvest
T1 – (Control-100 % RDF)	39.73	78.64	141.33	153.85
T2 – (75 % RDF + Vermicompost)	45.7	95.54	152.52	167.2
T3 – (50 % RDF + Vermicompost)	44.1	84.13	148.92	161.05
T4 – (75 % RDF + Rhizobium)	47.8	105.97	154.71	171.29
T5 – (50 % RDF + Rhizobium)	51.13	116.31	161.71	182.6
T6 – (75 % RDF + Vermicompost + Sulfur	58.36	127.99	172.24	197.54
T7 – (75 % RDF + Rhizobium + Sulfur)	53.36	123.6	165.14	185.07
SEM	0.58	0.99	0.084	0.25
C.D. at 5%	1.36	1.77	0.51	0.89

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

3.2. Effects of INM on Primary and Secondary Branches/Plants

Table 4 presents the data on primary and secondary branches per plant. The results demonstrate that regardless of the treatments, the number of primary and secondary branches per plant increases gradually as the crop grows. INM has a supplementary impact on the development of primary and secondary branches. The highest number of primary branches (9.3) was observed when utilizing T6, while the lowest number of primary branches (3.6) was found in the control (T1). Similarly, the highest number of secondary branches (12.3) was recorded with the utilization of T6, while the lowest number of secondary branches (6.6) was observed in the control (T1). Throughout all growth stages, the combined utilization of T6 and T7 resulted in the maximum number of primary and secondary branches. This may be attributed to the continuous availability of nutrients over the crop growth period, promoting efficient branching. Additionally, the favorable influence of nutrients on metabolism and biological activity, as well as their stimulatory effect on photosynthetic pigments and enzymatic activity, could contribute to the enhancement of vegetative growth in plants. Similar results were reported by ur Rehman et al. [19], where an increase in the number of primary branches per plant of two canola cultivars Shiralee and Dunkeld was observed up to 50 kg/ha of phosphorus and 40 kg/ha of sulfur.

Table 4. Efficacy of primary and secondary branches/plant of mustard as influenced by INM.

Treatments	Primary branches/plant	Secondary branches/ plant
T1 – (Control -100 % RDF)	3.6	6.6
T2 – (75 % RDF + Vermicompost)	4.6	7.6
T3 – (50 % RDF + Vermicompost)	4	7
T4 – (75 % RDF + Rhizobium)	5.6	8.6
T5 – (50 % RDF + Rhizobium)	6.6	9.6
T6 – (75 % RDF + Vermicompost + Sulfur)	9.3	12.3
T7 – (75 % RDF + Rhizobium + Sulfur)	7.6	10.6
SEM	0.32	0.32
C.D. at 5%	1.01	1.01

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

3.3. Effects of INM on Dry Matter Production

Based on the results presented in Table 5, INM had a significant impact on mustard dry matter production at the 30, 60, 90, and harvest stages. At 30 DAS, the highest dry matter production of 6.33 g was observed in T6, while the lowest dry matter production of 3.97 g was found in the control (T1). Similarly, at 60 DAS, the highest dry matter production of 10.37 g was recorded in T6, and the lowest dry matter production of 6.3 g was observed in the control (T1). At 90 DAS, the highest dry matter production of 19.91 g was obtained in T6, while the lowest dry matter production of 13.01 g was found in the control (T1). At harvest, the highest dry matter production of 15.81 g was in T6, and the lowest dry matter production of 18.22 g was recorded in the control (T1). All treatments showed significant differences compared to the control group. Notably, T2 and T3 were statistically similar in dry matter production.
The combined application in T7 resulted in higher total dry matter production at all growth stages. This could be attributed to the continuous availability of nutrients throughout the crop growth period, promoting efficient branching. The combination of Sulfur and vermicompost showed significant effects at 90 DAS and harvest, while it did not show a significant difference at 30 and 60 DAS. The favorable soil conditions may have facilitated greater root proliferation and nutrient uptake, accelerated the formation of new tissues, and consequently enhanced dry matter production. Similar findings were reported by Rundala et al. [20], where the use of 75% RDF along with farmyard manure (FYM) + 25% chemical fertilizers significantly increased dry matter production in mustard and was comparable to 50% RDF along with FYM + 50% chemical fertilizers. Singh et al. [21] also recorded that the treatment with 100% RDF + FYM 5 t/ha + vermicompost (VC) 2.5 t/ha + Azotobacter resulted in the highest dry matter yield of Indian mustard.

Table 5. Efficacy of dry matter production (g) at 30, 60, and 90 DAS and harvest as influenced by INM

Treatments	Dry Matter Production (g)			
	30 DAS	60 DAS	90 DAS	Harvest
T1 – (Control-100 % RDF)	3.97	6.3	13.01	18.22
T2 – (75 % RDF + Vermicompost)	4.78	7.67	15.49	20.36
T3 – (50 % RDF + Vermicompost)	4.1	7.08	14.52	19.88
T4 – (75 % RDF + Rhizobium)	5.15	7.80	16.58	21.51
T5 – (50 % RDF + Rhizobium)	5.56	8.28	17.64	23.59
T6 – (75 % RDF + Vermicompost + Sulfur)	6.33	10.37	19.91	25.81
T7 – (75 % RDF + Rhizobium + Sulfur)	6.04	9.38	18.57	23.71
SEM	0.12	0.23	0.07	0.09
C.D. at 5%	0.62	0.86	0.49	0.55

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

3.4. Effects of INM on Siliqua Yield Parameters of Mustard

As presented in Table 6, the highest siliqua length of 6.76 cm was observed in T6, while the lowest siliqua length of 5.03 cm was recorded in the control (T1). The increase in siliqua length could be attributed to the availability of sulfur and vermicompost, which promote soil microbial activity, enhance oxygen availability, improve nutrient content, maintain normal soil temperature, and ultimately increase the plant's yield. Similar results were reported by Ramana et al. (2010) in an experiment with the Arka Suvidha variety (V2), where the application of 75% RDF + VAM @ 2 kg/ha + PSB @ 2.5 kg/ha significantly increased the siliqua length (cm). The highest weight of siliqua per plant was 115.8 g in T6, while the minimum weight of siliqua per plant was 86.92 g in the control (T1). The highest number of seeds per siliqua (19) was observed with the application of T6, and the lowest number of seeds per siliqua (10) was recorded in the control (T1). The increase in the number of seeds per siliqua could be attributed to the overall improvement in plant growth, resulting in an increased photosynthetic rate. The availability of photosynthates, metabolites, and nutrients likely supported the development of reproductive structures, leading to a higher number of seeds per siliqua. These findings are consistent with those reported by Rundala et al. [20], where the application of 75% RDF along with FYM + 25% chemical fertilizers significantly increased the number of siliqua per plant and was comparable to the application of 50% RDF along with FYM + 50% chemical fertilizers in mustard.

Table 6. Efficacy of Siliqua length (cm), the weight of siliqua/plant (g), and Number of seeds/ siliqua as influenced by INM

Treatments	Siliqua length (cm)	Weight of siliqua/plant (g)	No. of seeds/siliqua
T1 – (Control 100 % RDF)	5.03	86.92	10
T2 – (75 % RDF + Vermicompost)	5.33	92.97	13
T3 – (50 % RDF + Vermicompost)	5.16	89.74	11
T4 – (75 % RDF + Rhizobium)	5.33	91.63	15
T5 – (50 % RDF + Rhizobium)	5.4	100.92	16
T6 – (75 % RDF + Vermicompost + Sulfur)	6.76	115.8	19
T7 – (75 % RDF + Rhizobium + Sulfur)	5.7	104.67	18
SEM	0.08	0.32	0.28
C.D. at 5%	0.52	1.01	0.95

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

3.5. Effects of INM on Seed Parameters of Mustard

As presented in Table 7, the highest seed weight per plant was 13.64 g in T6, while the lowest seed weight per plant was observed to be 7.75 g in the control (T1). The increase in seed weight per plant could be attributed to the continuous utilization of balanced NPK and sulfur throughout the crop growth period, along with good management practices. Similar results were reported by Meena et al. [11], where the use of Vermicompost @ 5.0 t/ha + 75 percent RDF resulted in the highest test weight in mustard compared to the utilization of FYM @ 10 t/ha + 75 percent RDF. The greatest number of seeds per plant (5320.33) was observed with the utilization of T6, and the minimum number (2489.66) was recorded in the control group (T1). The increase in this character could be attributed to the balanced nutrient application, which made higher nutrients available to the plants, leading to a higher accumulation of net photosynthesis with the optimum dose of NPK along with sulfur and Rhizobium over an extended period. Similar results were reported by Tripathi et al. [22] where applying 100 percent RDF + FYM @ 2 t/ha + 40 kg S + ZnSO4 @ 25 kg/ha + Boron @ 1 kg/ha + Azotobacter (seed treatment) to mustard at Pantnagar during the rabi season resulted in the highest number of siliqua per plant. The highest test weight of 6.26 g was observed in T6, while the lowest was 3.24 g in the Control group (T1). These findings are consistent with those reported by Ranjan et al. [23], who recorded the highest test weight (5.98 g) in mustard with the application of 75 percent RDF supplemented with 5 kg Zn, 30 kg S, along with the remaining 25 percent through FYM and PSB @ 2.5 kg/ha at Kanpur.

Table 7. Efficacy of Seed weight /plant (g), no. Of seeds/plant and test weight (g) of mustard as influenced by INM.

Treatments	Seed weight/ plant (g)	No. of seeds/plant	Test weight (g)
T1 – (Control 100 % RDF)	7.75	2489.66	3.24
T2 – (75 % RDF + Vermicompost)	9.7	2999.33	4.34
T3 – (50 % RDF + Vermicompost)	8.91	2639.33	3.75
T4 – (75 % RDF + Rhizobium)	10.66	3201.66	4.25
T5 – (50 % RDF + Rhizobium)	11.2	3397.00	4.89
T6 – (75 % RDF + Vermicompost + Sulfur)	13.64	5320.33	6.26
T7 – (75 % RDF + Rhizobium + Sulfur)	11.55	3906.33	4.71
SEM	0.09	0.37	0.06
C.D. at 5%	0.55	1.08	0.45

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

3.5. Effects of INM on Seed Yield, Stover Yield, Biological Yield, and Harvest Index of Mustard

As shown in Table 8, the highest seed yield of 1690 kg/ha was obtained in T6, while the minimum seed yield of 1120 kg/ha was observed in the control group (T1). Growth and yield characteristics are directly correlated with seed yield. The availability of nutrients and growth hormones may have increased nitrogen metabolism and protein synthesis in plant tissues, contributing to the increase in seed output. Increased crop production resulting from the combined use of chemical and organic fertilizers may have led to better utilization of the crop's genetic capacity for both vegetative and reproductive growth and maintained nutrient supply. The highest stover yield was observed in T6, while the least stover yield was recorded in the control (T1). The maximum biological yield of 6489 kg/ha was observed in T6, while the minimum biological yield of 5046 kg/ha was obtained in the control (T1). The best harvest index of 26.04 percent was recorded in T6, while the least harvest index of 22.19 percent was observed in the control group (T1). The influence of integrating chemical and organic sources of nutrients on the harvest index leads to higher percentages. Similar findings were reported by Kansotia et al. [24] experimented and revealed that the utilization of vermicompost @ 2.0, 4.0, and 6.0 t/ha resulted in higher biological yield (1680 kg/ha) of mustard.

Table 8. Efficacy of seed yield (kg/ha), stover yield (kg/ha), biological yield (kg/ha), and harvest index (%) as influenced by INM.

Treatments	Seed Yield (kg/ha)	Stover Yield (kg/ha)	Biological Yield (kg/ha)	Harvest Index (%)
T_1 – (Control 100 % RDF)	1120	3926	5046	22.19
T_2 – (75 % RDF + Vermicompost)	1247	4255	5502	23.12
T_3 – (50 % RDF + Vermicompost)	1211	4025	5236	22.66
T_4 – (75 % RDF + Rhizobium)	1382	4326	5709	24.2
T_5 – (50 % RDF + Rhizobium)	1460	4615	6075	24.03
T_6 – (75 % RDF + Vermicompost + Sulfur)	1690	4799	6489	26.04
T_7 – (75 % RDF + Rhizobium + Sulfur)	1572	4719	6291	24.98
SEM	0.83	0.68	1.69	0.001
C.D. at 5%	1.62	1.47	2.31	0.02

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

3.6. Effects of INM on Quality Parameters of Mustard

As shown in Table 9, T6 treatment resulted in significantly the highest (35.76%), while the control group (T1) had the lowest oil content (33.20%). The increase in oil content might be attributed to the increased availability of sulfur, which promotes the conversion of primary fatty acid metabolites to the end products of fatty acids. Among the various integrated nutrient management approaches, T6 resulted in significantly the highest oil yield (604 kg/ha), whereas the Control group (T1) had the lowest oil yield (371 kg/ha). Similar findings were reported by Sahoo (2018), showing that the oil yield in mustard increases with the utilization of 75 percent STR + FYM @ 5 t/ha + Azotobacter. The highest nitrogen content in mustard seeds was observed in T6, while the lowest nitrogen content was found in the control group (T1). Specifically, the nitrogen content was recorded as 6.86% in T6 and 4.64% in the control group (T1). The nitrogen content in the rest of the treatments ranged from 5.17% to 5.83%. The higher nitrogen content might be attributed to the continuous availability of NPK throughout the crop growth period. Similarly, the higher protein content in mustard seeds was observed in the T6 treatment, while the lowest protein content was found in the control group (T1). The higher protein content might be attributed to the continuous availability of NPK throughout the crop growth period [26, 27]. Similar findings were disclosed by Anil et al. [25] in a field study at Hisar (Haryana), reporting that applying 40 kg N + 20 kg P2O5/ha on the pearl millet crop increased the quality parameters.

Table 9. Oil content (%) and Oil yield (kg/ha) of mustard as influenced by INM.

Treatments	Oil content (%)	Oil Yield (kg/ha)	Nitrogen Content (%)	Protein Content (%)
T1 – (Control-100 % RDF)	33.20	371	4.64	29.03
T2 – (75 % RDF + Vermicompost)	33.71	420	5.40	33.76
T3 – (50 % RDF + Vermicompost)	33.50	405	5.17	32.30
T4 – (75 % RDF + Rhizobium)	34.24	473	5.59	34.93
T5 – (50 % RDF + Rhizobium)	34.71	506	5.77	36.10
T6 – (75 % RDF + Vermicompost + Sulfur)	35.76	604	6.86	42.87
T7 – (75 % RDF + Rhizobium + Sulfur)	35.23	553	5.83	36.45
SEM	0.01	0.003	0.13	
C.D. at 5%	0.22	0.60	0.10	0.65

RDF: recommended dose of fertilizer; DAS: days after showing; SEM: standard error of the mean; C.D.: critical difference at 5% level of probability.

4. Conclusion

In conclusion, the present research demonstrated the significant efficacy of integrated nutrient management (INM) in enhancing the growth, yield, and quality of Indian mustard (Brassica juncea L.). The study evaluated seven treatments, with T6, comprising 75% recommended dose of fertilizer (RDF) + vermicompost + sulfur, emerging as the most promising treatment. In contrast, the control treatment (100% recommended dose of fertilizer) demonstrated lower performance across all measured parameters, indicating the limitations of sole reliance on conventional fertilizers for maximizing crop yield and quality. Overall, the findings of this study emphasize the importance of adopting integrated nutrient management practices to achieve sustainable agriculture. By combining organic sources like vermicompost and beneficial microbes like Rhizobium with a reduced dose of chemical fertilizers, farmers can enhance crop productivity while minimizing environmental impacts. These results have significant implications for enhancing food security and economic prosperity for farmers engaged in mustard cultivation. Further research and adoption of such innovative agricultural practices could contribute to the sustainable intensification of mustard farming and potentially benefit other oilseed crops as well.

Funding Information: This work is not funded by any agency.

Acknowledgments: This research work is part of the first author's M.Sc. Thesis. The authors are highly thankful to the Department of Agriculture, Dev Bhoomi Uttarakhand University, Dehradun to provide the lab and field facility.

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not applicable.

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