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RESEARCH ARTICLE

Balanced fertilization for yield maximization, profitability and quality of Indian mustard (*Brassica juncea* L.) in North Western Himalayas

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Abstract

Indian mustard is one of the major oilseed crops of the country. The productivity of this crop is quite low compared to the rapeseed mustard crops in some other countries, such as Canada and Germany. One of the major reasons for lower productivity is the lack of balanced nutrition in many parts of the country. Sulphur (S), boron (B) and zinc (Zn) play an important role in the metabolism of Rapeseed mustard crops. A field experiment was conducted at Research Farm, SKUAST-Jammu in 2022 and 2023, to investigate the influence of different fertility levels with macro and micro nutrients on productivity, profitability and quality of Indian mustard. The treatment consisted of four fertlity levels containing $N:P_2O_5:K_2O$ doses *viz.,* F_1-control, F_2- 80:40:20 kg ha^{-1}, F_3- 100:50:25 kg ha^{-1}and F_4- 120:60:30 kg ha^{-1} respectively in main plots and four macro and micronutrient treatments namely, N_1- 20 kg S+2.5 kg Zn + 0.5 kg B, N_2- 40 kg S+ 5.0 kg Zn +1.0 kg B, N_3- N_1 + 500 kg FYM ha^{-1}, N_4- N_2+ 500 kg FYM ha^{-1} in sub plots, which were laid out in split-plot design and replicated thrice. The results revealed that the application of $N:P_2O_5:K_2O$ at 120:60:30 kg ha^{-1} in combination with 40 kg S+ 5.0 kg Zn +1.0 kg ha^{-1} B enriched with 500 kg FYM ha^{-1} recorded a significant increase in seed and oil yield along with yield attributes, nutrient uptake, soil microbial population, net returns and B:C ratio of Indian mustard than other treatments in comparison. A significant positive correlation was noted between seed yield and nutrient uptake.

Keywords: boron; farmyard manure; nutrient uptake; quality; rapeseed mustard; sulphur; yield

Introduction

In India, oilseeds are the second utmost vital crop after cereals. They are major sources of crucial fatty acids and vitamin E. After USA, China and Argentina, India is the fourth largest oilseeds producer with 10 % contribution to total global production. Rapeseed mustard crops are cultivated on an area of 41.95 million hectares worldwide, with the total production and productivity of 91.0 million tonnes and 21.10 tonnes per hectare respectively (1). In 2024, India imports 15 % of the world's edible oil and becomes the largest global purchaser of edible oils, with $16.5 billion in imports (2). In India, amongst all oilseed crops, rapeseed-mustard is one of the most important oilseed crops with maximum acreage in the country (3). The total oilseed production in the country is 39.59 million tonnes, out of which rapeseed mustard crops are the single largest contributor with 33.24 % share in the total oilseed production. However, the productivity in the country is quite low when compared to the leading rapeseed mustard producing countries, such as China, Germany, Canada besides other European countries where the per hectare productivity is more than 20 quintals per hectare average yield in comparison to 15 quintal per hectare average yield realized in the country so far.

In North western Himalayan region, the use of old and obsolete low yielding varieties, agronomic practices, water stress, delayed sowing, climate variability, early crop stage or terminal heat stress besides the imbalanced fertilization and non-application of secondary macronutrient like sulphur (S) and other micronutrients like boron (B) and zinc (Zn) on regular basis in the fields are the major causes of lower productivity of Indian mustard. The exclusive application of chemical fertilizers like Urea, Diammonium phosphate (DAP) and Muriate of Potash (MOP) results in depletion of soil quality and drastic reduction in crop yields owing to decreased factor productivity. Mustard crop is highly sensitive to the deficiency of sulphur, zinc and boron which is common in mustard growing areas of North western region and is the major constraint in achieving higher productivity. Thus, potential productivity of Indian mustard can only be achieved by balanced use of nutrients including secondary macro and micro-nutrients. Further, integration of different nutrients like nitrogen, phosphorus and potassium with macro and micro nutrients and farm yard manure (FYM) is pivotal for increasing the productivity in the country as it has a beneficial effect on the growth, yield and quality of Indian mustard. The enrichment of synthetic fertilizers with FYM have shown promising results in sustaining productivity. This act of bio-energizing helps in enhancing the activities of microbial population and soil physico-chemical properties through the increasing the mineralization process through direct release of macro and micro nutrients which resulted in increased crop yield (4). Also, sulphur is considered as the most important nutrient after nitrogen, phosphorus and potassium (5). It plays an indispensable role in formation of three important amino acids *viz.,* cysteine, cystine and methionine which are essential for protein synthesis and various metabolic activities in plant (6). Sulphur also participates in the activities of sulphydryl (SH-) linkages that are responsible for formation of Sinigrin, which is the root cause of pungency in oilseeds (7). Similarly, zinc is the first micronutrient to be recognized as crucial for plant. It plays a crucial role in stability of cytoplasmic ribosomes, cell division, dehydrogenase, proteinase and peptide enzymes and helps in the formation of protein and carotene (8). Better zinc nutrition of crop encouraged both primary and secondary branches, which results in higher seed and stover yield (9). Likewise, boron is the essential micronutrient which is needed by the crop for normal growth. It maintains proper water equilibrium within the plant and facilitates the fruiting processes. It is involved in the synthesis of both oil and protein. The other important functions of boron in plants are formation and stability of cell wall, maintenance of structural and functional integrity of the biological membranes and transportation of sugar products from source to sink (10). All these factors have necessitated research to determine FYM enriched, sulphur, zinc and boron levels in conjunction with different fertilizer levels for the supply of vital micro and macronutrients in order to provide meaningful recommendations to farmers in the region as it is expected to help in increasing the yield of Indian mustard in Jammu region significantly in the years to come in view of increasing area under cultivation of rmustard crop under Jammu conditions.

To ensure sustainable production of Indian mustard, it is vital to optimize nutrient management in this crop. In North western region, many agricultural soils face the problem of nutrient imbalance or deficiency specifically sulphur, zinc and boron. Therefore, the present investigation aimed to rectify this problem and provides the region-specific fertilizer recommendation which helps to empowering the farmer community to make informed decisions for their crop. This research also supports food security and contributes to the economic well being of farming communities in the North Western region.

Materials and Methods

The experiment was performed at the Oilseed Experimental Area, Research Farm, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu (Fig. 1), during the *rabi* season of 2022 and 2023 to study the effect of different fertilizer levels with macro and micronutrients on growth, productivity and quality of Indian mustard. Split Plot Design (SPD) was used with three replications. The net plot size was 5 m × 4.5 m. The crop was sown in lines 30 cm apart (row-to-row). The chemical fertilizers were applied as per

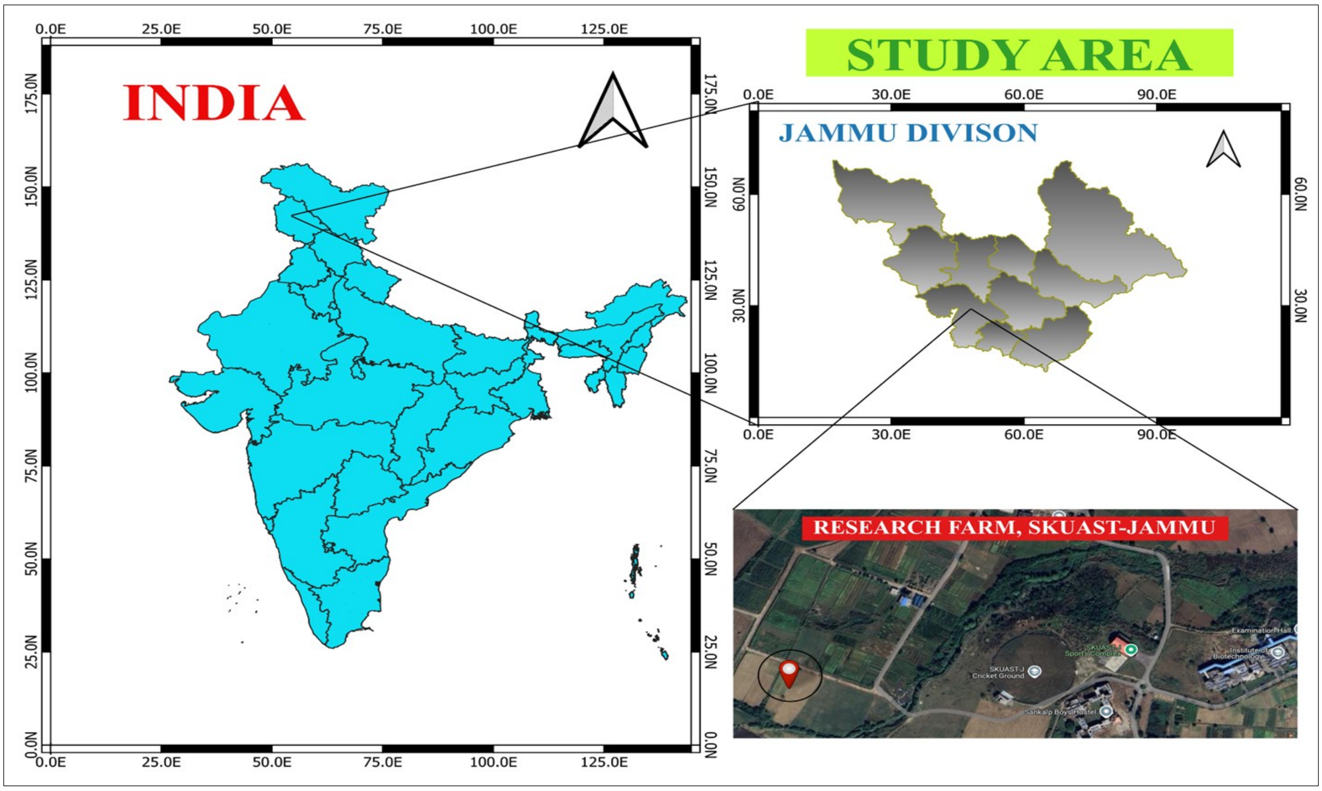

Fig. 1. Location map of the experimental site at Research Farm, SKUAST-Jammu (indicated as red location sign).

treatments *viz.,* 80:40:20, 100:50:25 and 120:60:30 kg NPK ha^{-1} for 100, 125 and 150 % fertility levels, respectively. The specific levels of nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) were chosen based on their initial levels of these nutrients in experimental field. The soil in the experimental field was low in organic carbon, available nitrogen and zinc but medium in available phosphorous, potassium, sulphur and boron, respectively. Therefore, the recommended dose of fertilizers were increased up to 150 % to examine whether the higher nutrients levels would contribute to an increase in the seed yield of mustard crop. Also, the mustard crop variety RH 725 used in the present study has a higher yield potential and require a higher dose of nutrient to achieve potential yield (11). Further, the levels of available zinc (Zn) and boron (B), their selection was based on low availability of these micronutrients in the experimental field, as well as some previous studies in the region that utilized almost similar levels (12, 13). The nutrient sources were urea, diammonium phosphate, muriate of potash, sulphur bentonite -90 % S, zinc sulphate monohydrate and borax, respectively. The required secondary macro and micronutrients as per the specified treatments namely sulphur, zinc and boron were enriched using farm yard manure at 500 kg ha^{-1} by mixing the fertilizers for 15 days in advance at the site for bioactivation. Frequent stirring of the mixture after every 3 days period was ensured for uniform mixing and microbial activation. The experimental treatments were as follow:

Treatments

Main plot treatments (Fertility levels)

F_1: Control

F_2: $N:P_2O_5:K_2O$ at 80:40:20 kg ha^{-1}

F_3: $N:P_2O_5:K_2O$ at 100:50:25 kg ha^{-1}

F_4: $N:P_2O_5:K_2O$ at 120:60:30 kg ha^{-1}

Sub plot treatments (Macro and micro nutrients)

N_1: 20 kg S+2.5 kg Zinc+0.5 kg Boron

N_2: 40 kg S+ 5.0 kg Zinc+1.0 kg Boron

N_3: 20 kg S+2.5 kg Zinc+0.5 kg Boron enriched with 500 kg FYM ha^{-1}

N_4: 40 kg S+ 5.0 kg Zinc+1.0 kg Boron enriched with 500 kg FYM ha^{-1}

Soil analysis

The soil analysis was done before applying the experimental treatments and after harvesting of mustard crop. Soil samples from each plot were randomly collected from a depth of 0-15 cm at five different spots within the plot. These samples were combined to form a composite sample for the experimental area, which was then air dried, ground into a fine powder and passed through a 2 mm sieve. The physico-chemical analysis of the experimental area is presented in Table 1.

Table 1. Physico-chemical properties of soil

Parameter		Values	
		Pre-sowing	
		2022-23	2023-24
Sampling depth	**Units**	**0-15 cm**	
pH		7.48	7.41
EC	dS m^{-1}	0.26	0.25
Organic carbon	g kg^{-1}	4.09	4.11
Nitrogen	kg ha^{-1}	147.03	147.36
Phosphorus	kg ha^{-1}	15.10	15.11
Potassium	kg ha^{-1}	118.04	119.56
Sulphur	kg ha^{-1}	28.01	27.98
Zinc	mg kg^{-1}	0.56	0.57
Boron	mg kg^{-1}	0.52	0.53
Soil Texture	Sandy clay loam		

Meteorological data

Weather data was acquired from the meteorological observatory located close to the experimental site at Research Farm, Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu, Jammu & Kashmir, India. The total amount of rainfall observed was 44.5 and 31.3 mm coinciding with the critical crop growth stages *viz.* flowering and siliquae formation and seed filling stage during both the crop growth period, respectively. Generally, lower temperature and higher relative humidity and rainfall were recorded in 2023 than 2022. The climatic conditions that existed during the growing period of crop as shown in Table 2.

Crop husbandry

The mustard variety RH-725 was sown manually on 22 October 2022 and 20 October 2023 using seed rate of 5 kg ha^{-1}. The crop was planted in rows spaced 30 cm apart. Only one irrigation was given to the crop at the initial stage in both years as the water received from rainfall at different growth stages was sufficient for the crop during both years of experimentation. The crop was harvested on 23 March 2023 and 22 March 2024, respectively, when 80 % of siliqua color turned yellowish. Harvesting was done manually using sickles. Immediately after harvesting of the crop, bundles were tied and tagged bundles were kept in plots for sun drying. After proper sun drying, threshing was done with the help to sticks and seed yield was noted plot wise using electronic balance.

Observations recorded and procedure for recording observations

Number of siliqua plant^{-1} : Siliquae were counted from five tagged plants and their mean value represented the Siliqua plant^{-1}.

Seeds siliqua^{-1}: Similarly, it was calculated by mean counts from five siliquae of each tagged plant.

1000-seed weight: A random sample of 1000 seeds from each net plot was weighed using a digital balance and noted in

Table 2. Meteorological data during the crop season

Month	2022-23					2023-24				
	Temperature (˚C)		Relative Humidity (%)		Rainfall (mm)	Temperature (˚C)		Relative Humidity (%)		Rainfall (mm)
	Max	Min	8 am	5 pm		Max	Min	8 am	5 pm	
October	30.3	13.65	85.9	43.15	0.0	29.8	14.3	89.7	48.5	0.0
November	25.05	9.3	91.12	48.45	6.2	25.6	10.4	91.4	52.2	18.2
December	20.92	5.55	92.95	51.9	2.4	21.2	5.7	95.9	53.7	0.8
January	15.7	4.8	95.1	71.8	4.9	12.5	4.7	95.8	77.1	0.0
February	23.6	7.7	89.5	53.0	8.2	20.7	5.6	92.9	52.7	10.5
March	27.0	12.3	90.1	50.3	9.6	25.1	9.3	89.3	45.0	15.0

grams.

Seed yield: The seed were threshed and cleaned from each net plot area. The value was attained in kg plot^{-1} then converted in kg ha^{-1} by given formula

$$\text{Seed yield (kg ha}^{-1}\text{)} = \frac{\text{Yield obtained from net plot (kg) x 10000}}{\text{Area of net plot}}$$

Oil content: First, seed samples were oven dried at 70 °C to eliminate moisture then crushed in a pestle-mortar and analyzed for oil content using the Soxhlet apparatus (14).

$$\text{Oil content} = \frac{\text{Weight of flask + petroleum ether extract - Weight of flask with oil}}{\text{Weight of sample (g)}} \times 100$$

Oil yield: It was calculated by multiplying oil content with seed yield of mustard using the formula:

$$\text{Oil yield (kg ha}^{-1}\text{)} = \frac{\text{Oil content (\%) x Seed yield (kg ha}^{-1}\text{)}}{100}$$

Nutrient uptake: Harvested samples were collected for nutrient analysis of N, P, K, S, Zn and B in seed and stover. After oven-drying, the plant samples were grinded and analyzed for N, P, K, S, Zn and B concentration. Nutrient uptake was calculated by multiplying nutrient concentration and dry matter accumulation (seed and stover).

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient content (\%) x dry matter accumulation (kg ha}^{-1}\text{)}}{100}$$

Available nutrients in soil

Nitrogen: It was determined using alkaline permanganate method (15). Processed soil is added to distillation flask along with 0.32 % $KMnO_4$ and 2.5 % NaOH. The resulting ammonia is captured in boric acid, which contains a mixed indicator of methyl red and bromocresol green adjusted to pH of 8.5. After that the collected solution was titrated with standard acid. It was expressed in kg ha^{-1}.

Phosphorus: Determined using Olsen's method with spectrophotometer at 660 nm and expressed in kg ha^{-1} (16).

Potassium: It was measured using neutral normal ammonium acetate solution and determined by flame photometer and expressed in kg ha^{-1} (17).

Sulphur: Assessed using calcium chloride (0.15 %) (18). It was determined by spectrophotometer at 420 nm and expressed in kg ha^{-1}.

Zinc: Determined using DTPA extract. It was analyzed by atomic absorption spectrophotometer and represented as mg kg^{-1}.

Boron: Quantified by the colorimetric Azomethine-H method (19). It was expressed as mg kg^{-1}.

Microbial population: Soil microbial population *viz.,* bacteria, fungi and actinomycetes were determined using the serial dilution agar plating method. The diluted samples were plated on respective media and incubated at 25±2 °C. For bacterial growth, incubation was carried out for 24 hr on Nutrient Agar Medium; for fungal growth, 7 days on Potato Dextrose Agar (PDA) whereas for actinomycetes it was kept for 7 days on Yeast Malt Agar (YMA). Colonies were counted, averaged and multiplied by the dilution factor to estimate microbial density per gram of soil (20).

Number of cells mL^{-1} or g^{-1} = Number of colonies (average of 3 replications) × Dilution factor

Dilution factor = Reciprocal of the dilution (e.g. 10^{-9} = 10)

Economics

Net returns: It was determined by subtracting total cost of cultivation from gross return and expressed as ₹ ha^{-1}.

B: C ratio: The benefit-cost ratio was calculated by dividing net returns by total cost of cultivation to identify the most cost-effective treatment.

Statistical analysis

The recorded data of both years were statistically evaluated using a two-way analysis of variance (ANOVA). Fisher's test of significance was used to compare significant treatment means at 5 % probability level. All statistical analyses were performed using OP STAT software and graphs were made by using MS Excel and R software version 4.2.2.

Results and Discussion

Yield attributes

Siliqua plant^{-1} was significantly affected by fertility levels and macro and micro nutrients during 2022 and 2023 cropping seasons. During 2022, the highest siliqua plant^{-1}, seeds siliqua^{-1} and 1000-seed weight was recorded in F_4 (348; 18.58; 4.62), followed by F_3 (328.33; 17.23; 4.38) and F_2 (245.50; 16.17; 3.97), respectively (Table 3). Whereas the lowest value was recorded under the control (F_1) treatment. Similarly, the maximum siliqua plant^{-1}, seeds siliqua^{-1} and 1000-seed weight was recorded under treatment F_4 (317.38; 17.80; 5.05), closely followed by F_3 (309.75; 17.65; 4.85) and F_2 (281.22; 15.37; 4.59), respectively and the least under the control (F_1) treatment during 2023. Higher nutrient availability was the major cause of improvement in yield attributes. Among the macro and micro nutrients, N_4 achieved significantly highest siliqua plant^{-1}, seeds siliqua^{-1} and 1000-seed weight, (285; 16.80; 4.14), respectively, than the rest of the treatments. Though the control was the least performing treatment in the year of 2022. During the second growing season, the maximum number of siliqua plant^{-1}, seeds siliqua^{-1} and 1000-seed weight were observed under the treatment N_4 (298.68; 16.57; 4.83) followed by N_3 (289.22; 15.98; 4.63), N_2 (267.92; 14.50; 4.43) and N_1 (258.93; 14.15; 4.32), respectively. Better availability of sulphur directly increased chlorophyll production, protein synthesis, carbohydrate metabolism and the translocation of photosynthates. The combined application of B and Zn also have beneficial effects on the reproductive parts of mustard (21-24). The interaction effect between the fertility levels and macro and micro nutrients in yield attributes was non-significant.

Table 3. Response of fertility levels and integrated nutrient management on yield attributes and yield of Indian mustard

Treatments	2022-23				2023-24			
	Number of siliqua plant^{-1}	Seeds siliqua^{-1}	1000-seed weight (g)	Seed yield (kg ha^{-1})	Number of siliqua plant^{-1}	Seeds siliqua^{-1}	1000-seed weight (g)	Seed yield (kg ha^{-1})
Fertility Levels								
F_1	184.25	12.73	2.76	980	206.40	10.38	3.71	1011
F_2	245.50	16.17	3.97	1466	281.22	15.37	4.59	1488
F_3	328.33	17.23	4.38	1608	309.75	17.65	4.85	1675
F_4	348.25	18.58	4.62	1698	317.38	17.80	5.05	1699
SEm(±)	6.75	0.43	0.10	28.23	5.84	0.37	0.10	34.22
LSD (0.05)	23	1.49	0.35	97	20.63	1.32	0.35	118
Macro and micro nutrients								
N_1	262.91	15.37	3.65	1242	258.93	14.15	4.32	1362
N_2	277.08	16.00	3.87	1325	267.92	14.50	4.43	1408
N_3	282.00	16.55	4.06	1569	289.22	15.98	4.63	1525
N_4	285.33	16.80	4.14	1617	298.68	16.57	4.83	1578
SEm(±)	3.06	0.14	0.03	32.97	3.86	0.22	0.09	18.62
LSD (0.05)	9	0.41	0.12	96	11.36	0.67	0.27	54
F × N	NS	NS	NS	NS	NS	NS	NS	NS

Seed yield

The different fertility levels and macro and micro nutrients have an essential role in increasing the seed yield of Indian mustard. Consequently, a higher seed yield (1698) was documented during the cropping season of 2022 in F_4, followed by F_3 (1608) and F_2 (1466) (Table 3), while a noticeable decrease in seed yield (980) was recorded in F_1 treatment as compared to other three treatments. Similarly, for the 2023 growing season, maximum seed yield was achieved in F_4 (1699) than in all other three treatments. Amongst macro and micro nutrients highest seed yield (1617) in 2022 was statistically achieved by treatment N_4 and treatment N_1 provided the lowest seed yield (1242) as compared to other treatments during 2022. In the growing season of 2023, maximum seed yield was observed under the treatment N_4 (1578), followed by N_3 (1525), N_2 (1408) and N_1 (1362). The significant increase in seed yield of Indian mustard was due to better growth and yield attributes through higher supply of major nutrients, which helped to compensate for the restricted nutrient availability. Also, micronutrients enriched with FYM may have affected the plant growth and development of Indian mustard during both the crop growing seasons. Moreover, the favourable rainfall and temperature during the flowering and seed formation stage in second crop growing season played a key role in higher crop growth and yield (25-28). Interaction between fertility levels and macro and micro nutrients in seed yield was non-significant.

Oil content

During 2022, oil content in treatment F_4 was increased to 38.67, whereas statistically minimum oil content was observed under the control treatment, in contrary to all other three treatments (Table 6). Consequently, maximum oil content was prominently obtained in treatment F_4 (38.79), followed by F_3 (38.19) and F_2 (37.46), while least oil content was recorded in F_1 (34.02) treatment during 2023. Application of NPK fertilizers may have activated the enzymes responsible for producing higher oil content in Indian mustard. A major enhancement in oil content (38.63) was attained under N_4 treatment as compared to rest of the treatments in the growing season of 2022. During 2023, higher oil content was obtained in treatment N_4 (38.74), followed by N_3 (38.14), N_2 (36.20) and N_1 (35.38). Sulphur has a significant role in increasing oil content and is vital for synthesis of fatty acid and oil synthesis. Similarly, zinc may have a role in enzymatic activation, which aids in more oil synthesis in the crop (16, 29). However, interaction between both the factors was non-significant.

Oil yield

Significantly maximum oil yield was noticed in treatment F_4 (657.56), followed by F_3 (615.89) and F_2 (551.66), while minimum oil yield (333.40) was attained from the control (F_1) treatment during the growing season of 2022. During 2023, again highest oil yield was recorded under F_4 (660.02) treatment. However, a significant decline in oil yield was noticed in F_1 (345.89) (Fig. 2) as compared to rest of the treatments. Among the macro and micro nutrients, the highest oil yield was attained in N_4 (630.27) in contrary to all other three treatments during 2022. The maximum oil yield (617.07) was statistically obtained in N_4, followed by N_3 (586.77), N_2 (515.45) and N_1 (488.14) during 2023. Oil yield in crops is influenced not just by seed yield but also by the biochemical processes governing oil synthesis, which are highly sensitive to nutrient balance and environmental stress. An adequate and balanced supply of macronutrients creates optimal conditions for seed formation. However, micronutrients also played a critical role in enhancing oil yield. Sulfur is directly involved in the synthesis of certain amino acids and enzymes essential for oil formation. Zinc and boron influence hormonal balance and cell division, which are vital during the flowering and seed development stages. Furthermore, boron facilitates the translocation of sugars and oils to the developing seeds. The enrichment of these micronutrients with FYM ensured a slow and steady release of nutrients, helping the plant maintain physiological functions. This not only supported higher seed formation but also improved oil content in those seeds, thus increasing total oil yield (30-32).

Nutrient uptake

The fertility levels, as well as macro and micro nutrients, have a major effect on nutrient uptake (N, P, K, S, Zn and B) of Indian mustard and bio-energizing farmyard manure with sulphur, zinc and boron at variable rates, which significantly increased the uptake of nutrients in the crop. However, maximum macronutrient uptake in respect of N, P, K and S (86.44; 19.01; 96.44; 20.46 kg ha^{-1}) and micronutrient uptake in respect of Zn and B (410.90; 173.52 g ha^{-1}) was recorded in

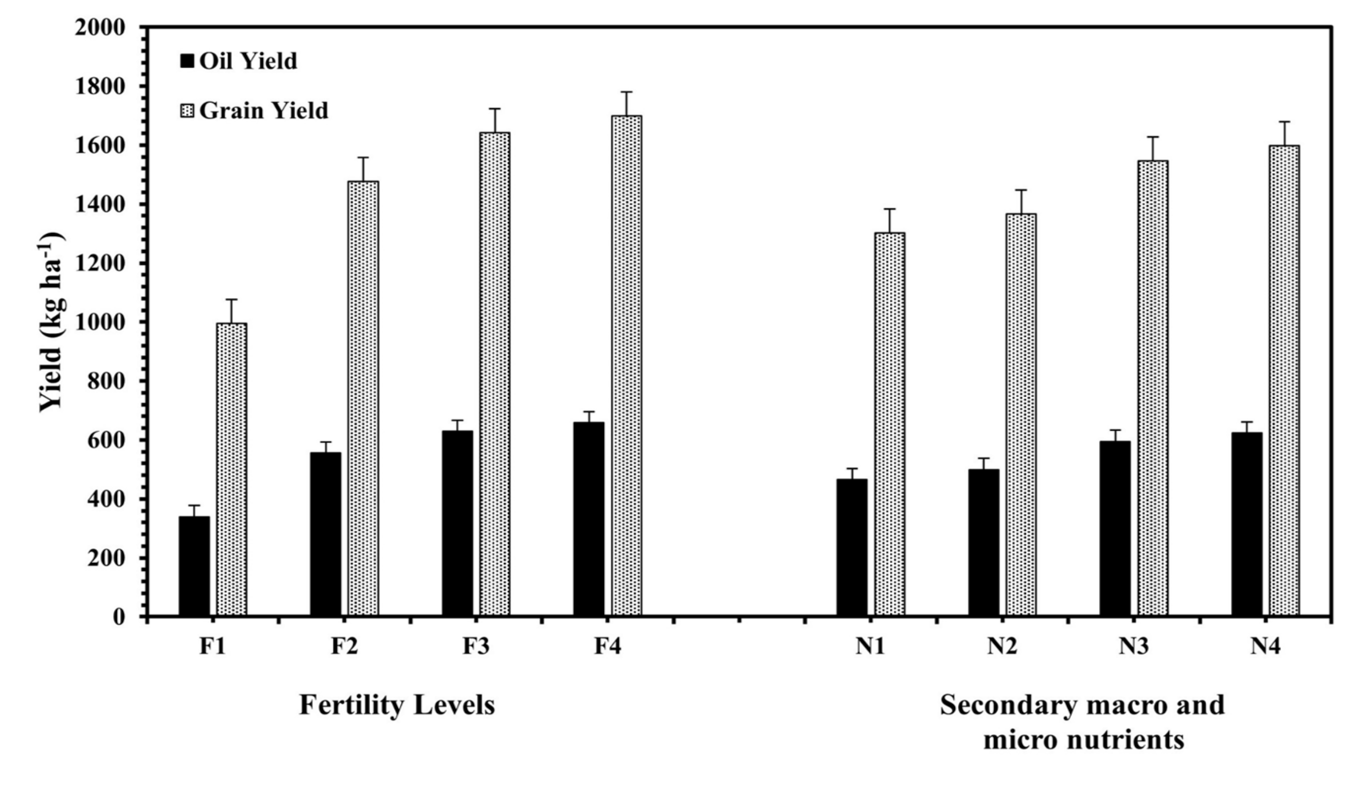

Fig. 2. Response of fertility levels and integrated nutrient management on oil yield and grain yield of Indian mustard.

Table 4. Response of fertility levels and integrated nutrient management on nutrient uptake of Indian mustard

Treatments	2022-23						2023-24					
	N	P	K	S	Zn	B	N	P	K	S	Zn	B
Fertility Levels												
F_1	39.72	8.74	49.72	12.43	259.17	113.23	43.47	9.30	51.22	13.12	261.97	114.70
F_2	79.02	17.38	89.02	18.89	387.75	161.71	84.02	17.98	90.52	19.69	390.55	163.31
F_3	81.39	17.90	91.39	19.39	395.14	165.48	86.39	18.50	92.89	20.19	397.94	167.08
F_4	86.44	19.01	96.44	20.46	410.90	173.52	91.44	19.78	98.10	21.38	413.95	175.28
SEm(±)	1.73	0.38	1.73	0.37	5.39	2.84	1.80	0.39	1.74	0.43	5.41	2.84
LSD (0.05)	6.00	1.31	6.00	1.30	18.62	9.80	6.23	1.37	6.03	1.28	18.67	9.82
Macro and micro nutrients												
N_1	67.90	14.93	77.90	16.98	351.63	147.35	71.65	15.50	79.40	17.66	354.43	148.81
N_2	70.02	15.40	80.02	17.44	358.23	150.80	75.02	16.00	81.52	18.24	361.03	152.40
N_3	73.50	16.17	83.50	18.21	368.97	156.57	78.50	16.77	85.00	19.00	317.77	158.17
N_4	75.15	16.53	85.15	18.56	374.13	159.57	80.15	17.30	86.82	19.47	377.18	160.99
SEm(±)	1.00	0.22	1.00	0.23	3.05	1.76	0.87	0.23	1.00	0.24	3.05	1.73
LSD (0.05)	2.92	0.64	2.92	0.68	8.90	5.16	2.56	0.67	2.93	0.77	8.92	5.07
F × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

N: Nitrogen (kg ha^{-1}); P: Phosphorus (kg ha^{-1}); K: Potassium (kg ha^{-1}); S: Sulphur (kg ha^{-1}); Zinc (g ha^{-1}); B: Boron (g ha^{-1})

treatment F_4 (Table 4) during 2022. A significant decrease in nutrient uptake was noticed under (F_1), respectively, from all the rest of the treatments. During 2023, the highest macronutrient uptake in respect of N, P, K and S (91.44; 19.78; 98.10; 21.38 kg ha^{-1}) and micronutrient uptake in respect of Zn and B (413.95; 175.28 g ha^{-1}) was observed in F_4 followed by F_3 and F_2 and lower nutrient uptake was recorded in F_1. Among the macro and micro nutrients, maximum N, P, K and S uptake (75.15; 16.53; 85.15; 18.56 kg ha^{-1}) and micronutrient uptake (374.13; 159.57 g ha^{-1}) was observed under the treatment N_4 whereas a minimum nutrient uptake was achieved in N_1 during the crop season of 2022. During 2023, again significantly highest uptake of N, P, K and S (80.15; 17.30; 86.82; 19.47 kg ha^{-1}) and Zn and B (377.18; 160.99 g ha^{-1}) was recorded in N_4, followed by N_3, N_2 and N_1. The essential macronutrients improved nutrient uptake by increasing their concentration in the soil, making them more accessible even in a smaller active root zone. In addition, application of FYM enhanced nutrient uptake efficiency. FYM contributes organic acids that help in the chelation and availability of micronutrients like zinc and boron. It also supports microbial activity, which facilitates the breakdown of organic matter and the release of nutrients. Moreover, FYM improves soil texture and water-holding capacity, creating a more favorable environment for root growth and nutrient absorption. These combined effects led to improved nutrient availability and uptake, which in turn supported better plant metabolism, higher yield and improved seed and oil quality (33-35).

Available nutrients in soil

After the harvest of the mustard crop, available macronutrient (N, P, K, S) and micronutrient (Zn and B) content of soil significantly increased with the combined application of fertilizers as per treatments, as well as macro and micro nutrients. The highest amount of available macronutrients with respect to N, P, K and S (151.25; 15.28; 123.34; 24.44) and micronutrients with respect to Zn and B (0.57; 0.56) were recorded under the treatment F_4 during 2022 (Table 5). Again, a similar trend was observed during 2023. Amongst macro and micro nutrients, maximum availability of macronutrients (150.47; 15.22; 123.04; 24.92 kg ha^{-1} N, P, K and S, respectively) and micronutrients (0.56; 0.55 g ha^{-1} Zn and B, respectively) was recorded under N_4, followed by N_3, N_2 and N_1 during 2022. Similarly, trend was observed in 2023. However, the interaction effect was found to be non-significant. The direct addition of N, P, K and micro nutrients in soil enhanced the availability of nutrients in soil pool (36-39).

Microbial population

The microbial population in the soil was significantly affected with fertility levels and macro and micro nutrients. The highest numerical value of bacteria, fungi and actinomycetes, respectively (5.88; 3.81; 2.63) were observed under fertility levels F_4 followed by F_3 (5.74; 3.57; 2.45) and F_2 (5.60; 3.47; 2.38) while lowest value were recorded under F_1 (5.33; 3.44; 2.30) during both the growing seasons. A significant increase in mean microbial population (bacteria, fungi and actinomycetes) was observed under N_4 (5.93; 3.83; 2.65), respectively, than the rest of the treatments during 2022 and 2023 (Fig. 3).

Economics

During 2022, F_4 gave maximum net returns and B: C ratio, the values being 68175 and 2.80, respectively followed by F_3 (64244; 2.74) and F_2 (57365; 2.55) whereas minimum net returns and B: C ratio (34542; 1.83) were obtained under control (F_1) treatment. Similarly, the highest net return and B: C ratio was recorded in F_4 (71664; 2.95) and the lowest were observed in F_1 (38222; 2.03), respectively, during 2023. Amongst macro and micro nutrients, N_4 gave the highest net returns and B: C ratio (64160; 2.64) than N_1 during 2022. In the growing season of 2023, again, maximum net return and B: C ratio were obtained in N_4 as compared to all other three treatments. This might be due to enhanced yield attributes and seed yield with lower cost of cultivation (6).

Principal component analysis (PCA) and correlation studies between yield attributes and nutrient uptake of Indian mustard

In 2022 (Fig. 4), PCA analysis discovered that the first and second principal components accounted for 95.81 % (fertility levels) and 2.51 % (Secondary macro and micro nutrients levels) of the variation in the yield attributes and nutrient uptake of Indian mustard, respectively. Similarly, during the second year, these components explained 97.70 % (fertility levels) and 1.65 % (Secondary macro and micro nutrients levels) of the changes in the yield parameters and nutrient uptake. Across both years, the results showed that increasing fertilizer rates from F_1 to F_4 marked a strong linear relationship with seed yield, siliqua plant^{-1}, seeds siliqua^{-1}, test weight, N, P, K, S, Zn and B uptake. This suggests that soil fertility management has a more substantial impact on the observed outcomes, whereas PC2 accounted small fraction of variance, likely linked to sub plot treatments (N_1-N_4). The minor contribution implies that differences in sulfur (S), zinc (Zn), boron (B) and FYM application play much smaller roles compared to fertility levels. Moreover, the maximum increase in yield attributes of mustard was recorded under the treatment combination of F_4N_4, than the rest of the treatments.

Table 5. Response of fertility levels and integrated nutrient management on available nutrients in soil

Treatments	2022-23						2023-24					
	N	P	K	S	Zn	B	N	P	K	S	Zn	B
Fertility Levels												
F_1	145.67	14.87	120.24	23.45	0.52	0.51	145.91	15.18	120.46	22.63	0.54	0.52
F_2	146.39	15.12	122.56	23.75	0.53	0.52	147.83	15.48	123.80	23.72	0.56	0.53
F_3	148.85	15.17	122.70	24.37	0.56	0.54	150.33	15.49	123.94	24.67	0.58	0.55
F_4	151.25	15.28	123.34	24.44	0.57	0.56	152.74	15.57	124.59	24.80	0.59	0.57
SEm(±)	1.17	0.08	0.63	0.20	0.01	0.004	1.15	0.07	0.61	0.25	0.01	0.004
LSD (0.05)	NS	NS	NS	0.70	0.02	0.01	NS	NS	NS	0.79	0.03	0.01
Macro and micro nutrients												
N_1	144.96	15.00	121.41	23.10	0.53	0.51	146.38	15.33	122.64	23.41	0.53	0.53
N_2	147.61	15.09	122.18	23.54	0.54	0.53	149.07	15.43	123.42	23.86	0.57	0.54
N_3	149.11	15.13	122.20	24.45	0.55	0.54	150.58	15.43	123.44	24.81	0.58	0.57
N_4	150.47	15.22	123.04	24.92	0.56	0.55	151.97	15.54	124.29	25.34	0.59	0.58
SEm(±)	1.48	0.04	0.37	0.17	0.01	0.006	1.47	0.03	0.36	0.16	0.01	0.005
LSD (0.05)	NS	NS	NS	0.50	0.02	0.01	NS	NS	NS	0.52	0.03	0.01
F × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

N: Nitrogen (kg ha^{-1}); P: Phosphorus (kg ha^{-1}); K: Potassium (kg ha^{-1}); S: Sulphur (kg ha^{-1}); Zinc (mg kg^{-1}); B: Boron (mg kg^{-1})

Table 6. Response of fertility levels and integrated nutrient management on oil content (%), net return (₹ ha^{-1}) and B:C ratio

Treatment	2022-23			2023-24		
	Oil content	Net return	B: C ratio	Oil content	Net return	B: C ratio
Fertility Levels						
F_1	33.90	34542	1.83	34.02	38222	2.03
F_2	37.35	57365	2.55	37.46	61558	2.74
F_3	38.11	64244	2.74	38.19	71227	3.05
F_4	38.67	68175	2.80	38.79	71664	2.95
SE m(±)	0.53	1539	0.07	0.53	1934	0.09
LSD (0.05)	1.85	5311	0.25	1.84	6674	0.31
Macro and micro nutrients						
N_1	35.27	47038	2.25	35.38	56301	2.69
N_2	36.08	49265	2.12	36.20	56612	2.43
N_3	38.05	63864	2.91	38.14	64530	2.95
N_4	38.63	64160	2.64	38.74	65228	2.69
SEm(±)	0.32	1797	0.08	0.31	1052	0.05
LSD (0.05)	0.94	5247	0.23	0.95	3072	0.15
F × N	NS	NS	NS	NS	NS	NS

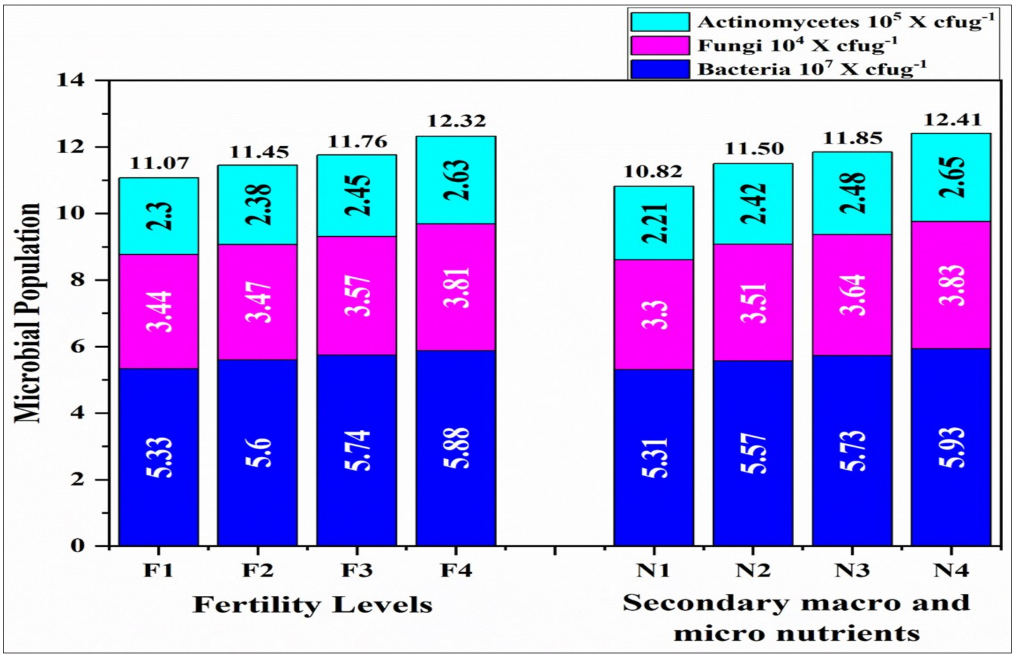

Fig. 3. Response of fertility levels and integrated nutrient management on total mean microbial population of Indian mustard.

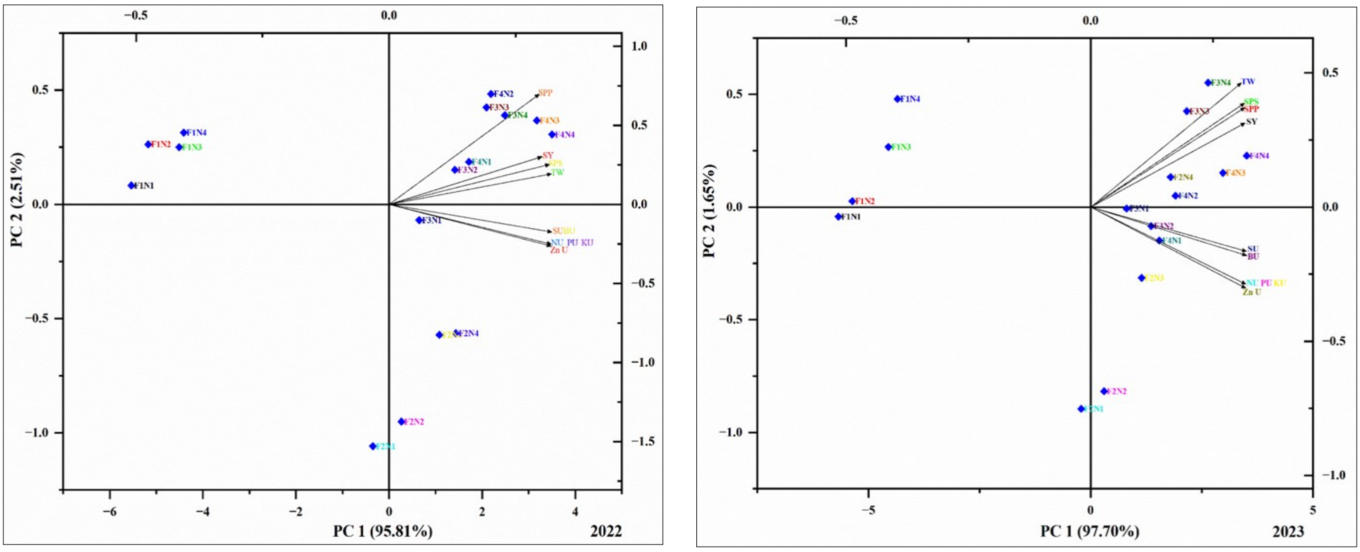

Fig. 4. Principal component analysis (PCA) among yield attributes and nutrient uptake of Indian mustard. SY: Seed yield; SPP: Siliqua plant^{-1}; SPS: Seed siliqua^{-1}; TW: Test weight; NU: Nitrogen uptake; PU: Phosphorus uptake; KU: Potassium uptake; SU: Sulphur uptake; ZnU: Zinc uptake and BU: boron uptake

In 2022 and 2023 (Fig. 5 & 6), Pearson's correlation analysis demonstrated a significant positive correlation among seed yield, siliqua plant^{-1}, seeds siliqua^{-1}, test weight, N, P, K, S, Zn and B uptake. The linear regression graph containing mean values for both the years of experimentation pertaining to nutrient uptake presented in Fig. 6 revealed that a mean positive correlation (r= 0.94, 0.94, 0.94, 0.93, 0.95 and 0.95) between seed yield and N, P, K, S, Zn and B uptake respectively was observed.

Conclusion

Based on the above results after two years of experimentation, it may be concluded that F3 (N:P2O5:K2O at 100:50:25 kg ha^{-1}) when supplemented with application of N3 (20 kg S+ 2.5 kg Zinc+ 0.5 kg Boron enriched with 500 kg FYM ha^{-1}) was found to be the most economical treatment which resulted in significant increase in the nutrient uptake of nitrogen, phosphorus, potassium, sulphur, boron and zinc and increased the seed yield significantly due to higher yield attributing characters than other treatments and hence may be recommended for getting higher and sustainable seed yield of Indian mustard in North Western Himalayan region of India.

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Authors' contributions

RB and VB wrote the original manuscript and prepared tables and figures. SK, MG and DC reviewed the manuscript. BK, SKR and NP participated in the sequence alignment. All authors read and approved the final manuscript.

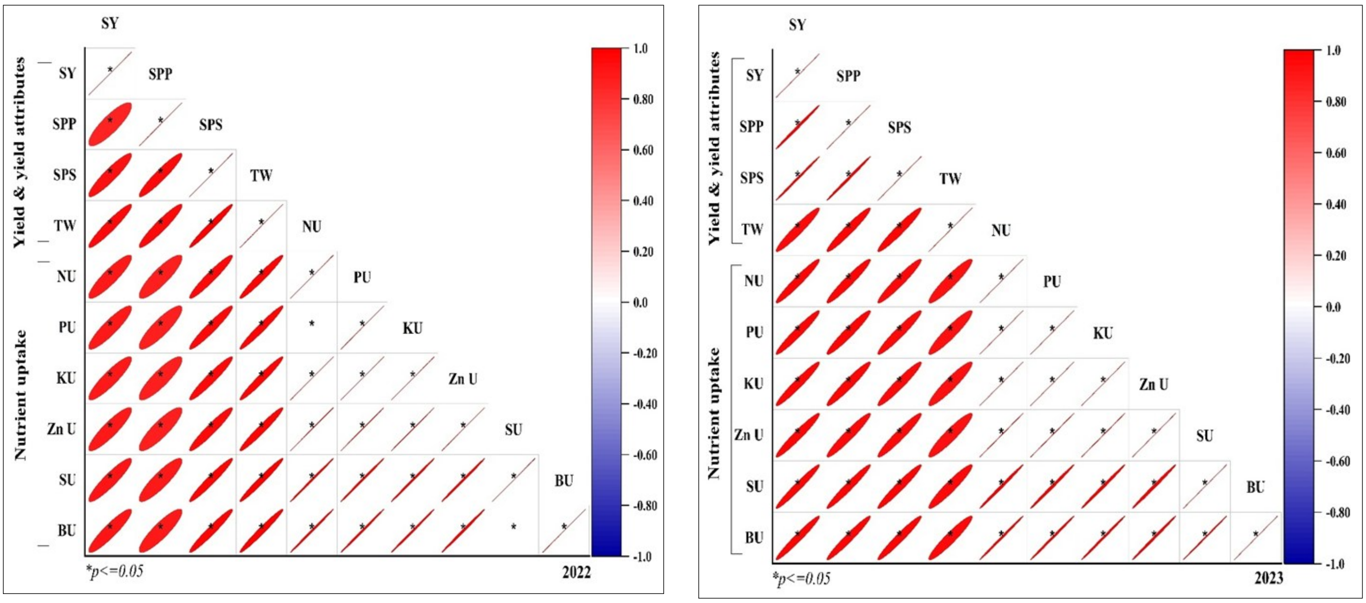

Fig. 5. Pearosn’s correlation between yield attributes and nutrient uptake of Indian mustard. SY: Seed yield; SPP: Siliqua plant^{-1}; SPS: Seed siliqua^{-1}; TW: Test weight; NU: Nitrogen uptake; PU: Phosphorus uptake; KU: Potassium uptake; SU: Sulphur uptake; ZnU: Zinc uptake and BU: Boron uptake.

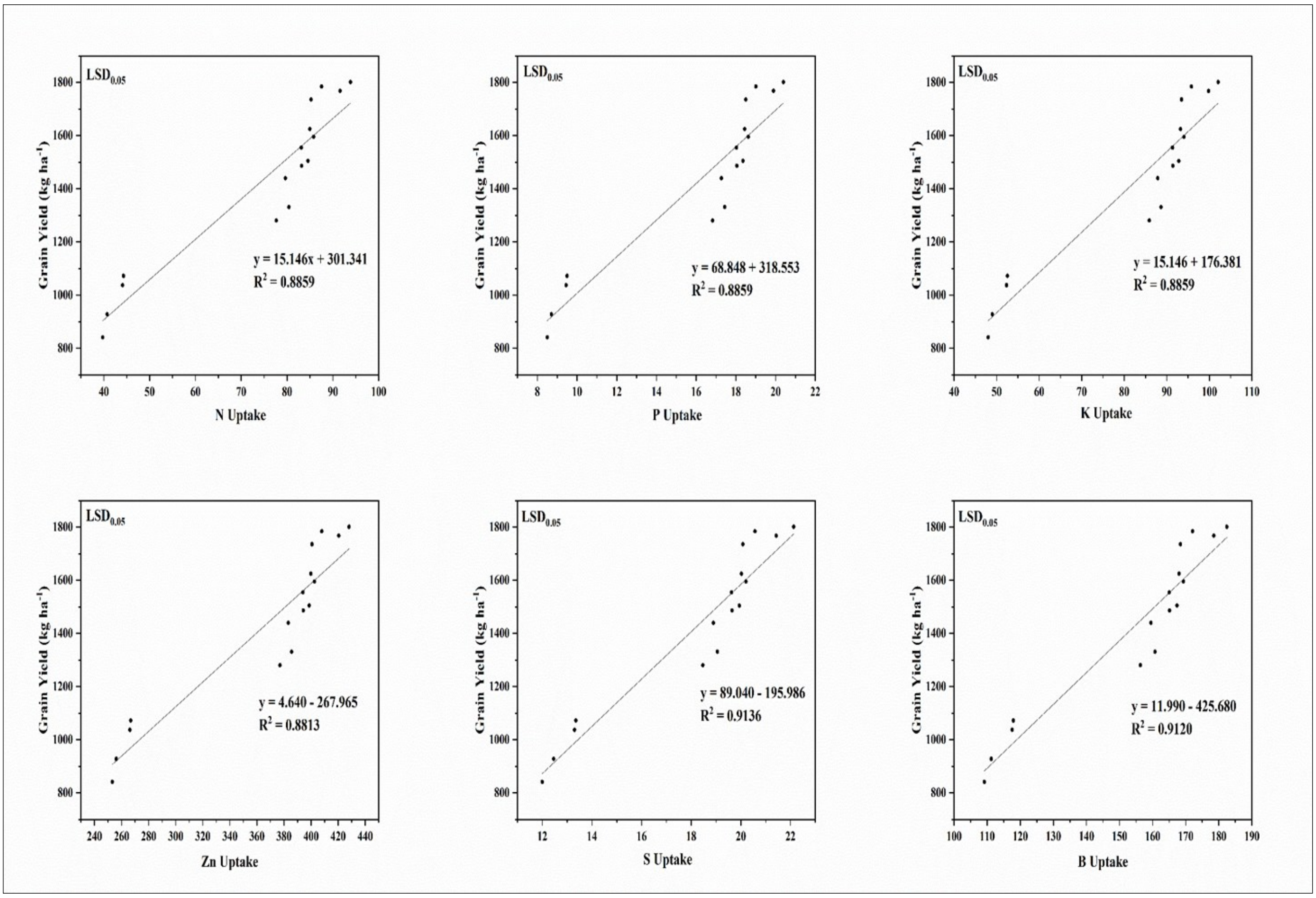

Fig. 6. The correlation between mean grain yield and mean nutrient uptake (kg ha^{-1}) of Indian mustard under different fertility levels and integrated nutrient management.

Compliance with ethical standards

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

Ethical issues: None

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