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RESEARCH ARTICLE

Optimization of INM strategies for enhancing growth and yield attributes of hexaploidy wheat (*Triticum aestivum* L.)

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Abstract

The study examined the productivity of wheat under integrated nutrient management employing inorganic, organic and bio-fertilizers over the course of two consecutive Rabi seasons in 2022-2023 and 2023-2024. During the Rabi season, the experiment was planned to use a Randomized Complete Block Design (RCBD) for wheat "HD 2967" (Wheat variety) was planted during November with twelve treatments. These included: T_1 - absolute control (no fertilizer), T_2 - 100 % recommended dose of fertilizers (RDF) through chemical sources and T_3 to T_{12} - combinations of RDF (100 %, 75 %, or 50 %) with vermicompost (VC), poultry manure (PM) and biofertilizers (Azotobacter, PSB, KMB, ZSB, or NPK consortia). Pooled data indicated application of T_9-75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZSB resulted in highest plant height (98.26 cm), leaf area index (LAI) (4.72), dry matter (m^{-2}) (1198.76 g m^{-2}), number of spike (m^{-2}) (307), spike length (10.51 cm), test weight (40.15 g), number of grains spike^{-1} (46.52), grain yield (5.39 t ha^{-1}), straw yield (12.81 t ha^{-1}) and harvest index (42.14 %).

Keywords: biofertilizer; HD-2967; nutrient management; wheat; yield

Introduction

The world's most significant food crop is Hexaploid wheat (*Triticum aestivum* L.), commonly known as bread wheat, contains six sets of chromosomes (2n=6x=42). Approximately 220 million hectares of wheat is grown worldwide, with a record production of 763 million tons (1). It is the staple food for 35 % of the world's population. China is the highest producer of wheat in the world with a production of 134 million tonnes which accounts for 20.7 % of the world's wheat production followed by India, Russia and the USA (2). Wheat is India's second-most significant cereal crop, which is essential to the nation's food and nutritional security. In India, it accounts for 14 per cent of global wheat area (30.5 m ha) and 13 per cent of global wheat production (108.8 million tonnes). Approximately 9.7 million hectares of wheat have been cultivated in Uttar Pradesh, yielding 26.9 million tons and 2786 kg/ha of productivity followed by Punjab, Haryana and Madhya Pradesh (3). Wheat is a temperate and sub-temperate region crop. It is grown in a wide range of temperatures, requires 600-900 mm annual rainfall, from sandy loam or loam texture, good structure and moderate water holding capacity. About 21 % of our entire caloric intake is supplemented by it, which also includes 10-12 % protein, 60-68 % carbohydrate, 1.5 % fat, 2.5 % cellulose and 1.5 %-2 % minerals.

Globally, there aren't many natural resources, mostly agricultural lands. More food grains must be produced by agriculture on a smaller amount of cultivable land in order to meet the growing population's demand for food (4). The eastern region's crop productivity is poor, ranging from 0.5 to 2.5 t ha^{-1} with an average of 1.5 t ha^{-1}. There is tremendous strain on the current farming system to meet the rising demand for food due to factors including population growth, consumption of food and the loss of arable land and other supply units. Crop growers are shifting to a balanced use of synthetic and organic fertilizers in order to combat this issue and achieve higher yields (5).

The primary cause of the nation's low wheat yield, among a number of biotic and abiotic stresses, is the high cost of inputs, mostly fertilizers, along with inadequate or non-existent micronutrient application. The utilization of balanced nutrients (by combining farmyard manure, compost, humic acid, etc. with synthetic fertilizers) is the primary tool for good crop production, according to research on wheat nutrition management (5). By increasing the soil's ability to hold water and nutrients, the addition of organic fertilizers increases bioactivities beneath the soil's surface, reducing soil crust and moisture/nutrient losses. The authors (6-8) reported that while simultaneous application of organic and chemical sources is a good technique in boosting crop fertility, quality and yield, integrated plant nutrients management has a great deal of potential for yield stabilization. Earlier studies (9, 10) found that applying Nitrogen, Phosphorus, Potassium and micronutrients together significantly increases yield, particularly in soils lacking organic matter, nitrogen, phosphorus and micronutrients. The quantity and quality of various plant products are impacted by such trace element deficiencies (11).

Application of imbalanced or excessive use of chemical fertilisers led to decline in partial factor productivity disturbed the physico-chemical properties of soil, causing adverse effects on the environment and impairing the groundwater quality, which causes health hazards in a changing climate scenario and thus making fertiliser consumption uneconomical (12). In addition to causing the loss of essential soil flora and fauna, the ongoing and careless use of inorganic fertilizers has also led to the loss of secondary and micronutrients (13). Integration of organic sources and bio-fertilisers may help in the restoration of soil health and quality food production. Besides, INM is also a key component for marginal and small farmers who cannot afford to supply crop nutrients through costly chemical fertilizers. Organic material recycling can improve the land, air, water and human health. By reducing waste and recycling, greenhouse gas emissions are avoided, pollutants are decreased, energy is saved, resources are preserved and fewer new disposal facilities are required. Organic matter has been shown to enhance soil health, increase the soil's phyto-availability of nutrients and improve soil structure (14). Cereals grown consecutively on the same plot of land in the same year cause an imbalance in the fertility of the soil, which lowers the output of both crops. It has been discovered that using organic, inorganic and biofertilizers in varying amounts shows promise for both sustaining increased productivity and enhancing crop production stability. At present, farmers mostly use arm yard Manure (FYM) and vermicompost in the wheat crop, but they have low nutritional value (NPK) and require a large quantity. Nowadays, the demand for chicken meat and eggs is increasing and poultry farming is growing rapidly day by day therefore, farmers have adopted poultry farming as a component of their income source. Poultry farms generate huge quantity of poultry manure and have high nutritional value as compared to other manures. Poultry manure improves soil fertility status, increases soil organic matter, increases soil biota activity and increases soil water-holding capacity when applied properly. It enhances soil structures, nutrient retention, aeration, soil moisture holding capacity and water infiltration by adding organic matter to the soil as opposed to chemical fertilizer (15). An excellent substitute for artificial fertilizer is poultry manure, which is a useful fertilizer. Different genera of microorganisms known as phosphate-solubilising microorganisms (PSM) convert insoluble organic phosphorus compounds into soluble ones. It was reported that bio-fertilisation technology minimises production cost and at the same time avoid the environmental hazards (16) .

Overall, INM fosters sustainable agriculture by reducing chemical fertilizer dependency and supporting ecosystem health (17). Therefore, the current study was designed to determine the best combination for restoring soil nutrients by INM and its impacts on wheat growth and yield characteristics.

Materials and Methods

The present field experiment was conducted during the *rabi* seasons of 2022 and 2023 at the Agronomy Research Farm of Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya (Uttar Pradesh), to study the performance of wheat under integrated nutrient management (INM). The purpose of the study was to assess how different combinations of chemical fertilizers, organic manures and biofertilizers influence wheat growth, yield and soil health. INM is gaining importance as a sustainable approach that enhances nutrient use efficiency while minimizing environmental impacts. The experiment was laid out in a Randomized Block Design (RBD) with twelve treatments, each replicated three times. The wheat variety used was HD-2967, a high-yielding, rust-resistant, semi-dwarf variety developed by the Indian Institute of Wheat and Barley Research (IIWBR), Karnal. It is well -suited for timely sown, irrigated conditions and is widely cultivated across northern and eastern India due to its stability and adaptability.

The treatments included a range of nutrient management options. The first treatment (T1) served as an absolute control, where no fertilizers were applied. The second treatment (T2) received 100 % of the Recommended Dose of Fertilizers (RDF) using chemical sources at the rate of 120 kg nitrogen, 60 kg phosphorus and 40 kg potassium per hectare. In the third treatment (T3), 100 % RDF was supplemented with biofertilizers including *Azotobacter*, phosphate solubilizing bacteria (PSB), potassium mobilizing bacteria (KMB) and zinc solubilizing bacteria (ZSB). The fourth treatment (T4) received 100 % RDF along with a consortia of NPK-specific biofertilizers. In the fifth and sixth treatments (T5 and T6), 75 % of the recommended fertilizers were applied chemically, while the remaining 25 % of nitrogen was substituted through vermicompost at 2 tonnes per hectare in T5 and poultry manure at 1 tonne per hectare in T6. Treatments T7 and T8 also received 75 % RDF along with vermicompost (2 t/ha), but in T7, this was combined with individual biofertilizers (*Azotobacter*, PSB, KMB and ZSB), while in T8, NPK microbial consortia were added instead. Similarly, treatments T9 and T10 received 75 % RDF with poultry manure (1 t/ha), where T9 included the individual biofertilizers and T10 was combined with NPK consortia. The final two treatments, T11 and T12, involved a reduced dose of 50 % RDF along with both vermicompost (2 t/ha) and poultry manure (1 t/ha). In T11, the combination included individual strains of biofertilizers and in T12, NPK consortia were used.

This comprehensive design was intended to examine the impact of integrating chemical fertilizers with organic and biological nutrient sources on the overall productivity and sustainability of wheat cultivation in the region.

Five randomly chosen plants in each plot provided data on yield metrics at harvest, which were then averaged to produce replicated data. The plant height, leaf area index (LAI) at 90 DAS, Crop growth rate at 60-90 days after sowing and dry matter Accumulation were the growth attributes measured. Grain yield, straw yield, harvest index, number of tillers per square meter and number of grains per spike were all collected as wheat yield characteristics.

Plant height

Plant height was measured by randomly selecting five plants from each plot. The height of each selected plant was recorded from the base to the tip of the tallest leaf or spike (as per growth stage) and the average of these five measurements was taken to represent the plant height for that treatment.

Leaf area index (LAI)

At 90 days after sowing (DAS), five plants were chosen at random from each plot and the leaf area was measured with a leaf area meter. The average leaf area per plant was calculated to determine the leaf area. The LAI was then calculated by dividing this average leaf area by the plant's ground area or spacing.

$$LAI = \frac{\text{Total area of leaf surface per plant}}{\text{Ground area occupied by plant}}$$

Crop growth rate (CGR) & Relative growth rate (RGR)

A plant's mean crop growth rate for a given time "t" is determined by measuring the increase in dry weight of plant material from a unit area over a unit of time.

$$CGR\ (g/m2/day) = \frac{W2-W1}{t2-t1} \times \frac{1}{A}$$

The calculated Mean Relative growth rate of a plant for a time "t" is defined as the increase in dry weight in unit time over the unit original weight of the plant.

$$RGR\ (mg/g/day) = \frac{\log W2-\log W1}{t2-t1} \times 1000$$

W1 = Total dry matter accumulation of the plant at time t1

W2= Total dry matter accumulation of the plant at time t2

T1=Time at first observation

T2=Time at second observation

A= Area of ground (m^2)

Dry matter production (m^{-2})

From each treatment, five hills were chosen at random. After being separated, the leaves, stems and roots were oven-dried for 24 hrs at 60 ± 5 °C. The dry weight of every component-aside from the roots, was added up, averaged and then multiplied by the population per square meter to get grams per square meter.

No. of tillers (m^{-2})

At harvest, the number of tillers on each of the five randomly selected hills from each treatment was tallied. For that treatment, the number of plants per square meter was multiplied by the mean number of tiller $hills^{-1}$.

Number of grains per spike

The number of grains was then counted after ten spikes were removed from each plot. Then, for each treatment, the average number of grains per spike was determined.

For grain and straw yield, firstly following threshing, the yields of grain and straw were measured independently for each treatment and reported in tons per hectare (t ha^{-1}).

Harvest index (%)

To calculate the Harvest Index, the following formulas were used:

$$HI = \frac{\text{Grain yield}}{\text{Grain yield + Straw yield}} \times 100$$

Soil Microbial Population

For microbial isolation, particular culture media were made, such as potato dextrose agar for fungi, actinomycete isolation agar for actinomycetes and nutrient agar for bacteria. The serial dilution and plate count methods were used to calculate the total counts of soil bacteria, actinomycetes and fungi. The following formula was used to determine these microbial populations per gram of dry soil:

$$\text{Total population per gram of oven dry soil} = \frac{\text{Number of colonies x Dilution factor}}{\text{Dry weight of one gram moist soil}}$$

Soil organic carbon content

Soil organic carbon content was estimated using the Walkley and Black rapid titration method. In this procedure, 1.0 g of air-dried, sieved soil sample was treated with 10 mL of 1 N potassium dichromate ($K_2Cr_2O_7$) solution and 20 mL of concentrated sulfuric acid (H_2SO_4). The mixture was allowed to stand for 30 min to ensure complete oxidation of the organic matter. Subsequently, 200 mL of distilled water and 10 mL of orthophosphoric acid were added, followed by titration with 0.5 N ferrous ammonium sulfate (FAS) solution using diphenylamine as an indicator. The amount of organic carbon was calculated based on the volume of FAS consumed (18).

Correlation Analysis

To investigate the relationships among various growth and yield parameters, correlation analysis was carried out using KAU Grapes software. KAU Grapes is a statistical software package developed by Kerala Agricultural University (KAU) specifically designed for agricultural research data analysis. The data collected from all treatments were analyzed to calculate Pearson's correlation coefficients, which helped in understanding the strength and direction of associations between traits such as plant height, grain yield and nutrient uptake. The software provided the correlation values along with significance tests, enabling identification of important traits that influence wheat productivity under integrated nutrient management.

Results and Discussion

Impact of integrated nutrition management on wheat growth characteristics: At harvest in 2022 and 2023, the maximum plant height (97.50 cm and 99.01 cm) was obtained under treatment with the 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9). As presented in Table 1, the control group (no fertilizer) had the lowest plant height at harvest in both years, measuring 64.55 cm and 63.12 cm. As indicated in Table 1, the combination of 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) produced the highest mean plant height (98.26 cm), while the control (no fertilizer) produced the lowest mean plant height (63.89 cm). In comparison to the control, the plants' height increased dramatically as they grew older.

Since nitrogen is a necessary element that probably improves photosynthesis and, as a result, plant height, it helps to raise the amount of chlorophyll at all growth stages. The increased availability and steady release of nutrients from organic sources like PM (poultry manure) may be the cause of the notable rise in plant height. These nutrient sources might aid in the growth and recuperation of plants, especially as they approach the reproductive stage. Plant height is positively impacted by an adequate supply of plant nutrients (19). The use of a combination of inorganic fertilizer and PM in addition to biofertilizers may have increased the plant's metabolic and physiological activity, allowing for better nutrient assimilation and growth and this could be the reason for the observed maximum plant height. Increased nutritional availability may also have resulted from integrated nutrient management methods, which would have improved meristematic cellular processes like cell division and elongation and made it easier for carbohydrates to be converted into proteins. Increased plant height is one quantifiable growth trait that results from this cellular activity and it eventually causes a bigger buildup of dry matter. Similar results have been documented before (20).

The LAI increased until 90 days after seeding, at which point it decreased. Among different treatments, highest LAI at 90 DAS (4.68 and 4.75) was obtained with 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZSB (T-9) in both years (2022 and 2023) followed by 75 % RDF + VC @ 2 t/ha + Azotobacter + PSB +KMB + ZSB (T7) (4.49 and 4.56). The lowest LAI (2.77 and 2.62) was recorded with the control. Higher mean LAI was obtained with 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZSB (T-9) (4.72) whereas the lowest mean LAI (2.70) was recorded with the control as depicted in Table 1.

Among many treatments, 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZSB (T-9) resulted in highest CGR values (15.91, 16.11 and 16.01) (during 2022, 2023 as well as pooled) and RGR values (22.56, 22.56 and 22.46) at 60-90 DAS (during 2022, 2023 as well as pooled). Similarly the lowest CGR values (6.14, 6.19 and 6.16) and RGR values (14.08, 14.75 and 14.41) at 60-90 DAS were noted for both years along with the mean, as showed in Table 2.

Crop growth rate is mostly determined by the development of leaf area. Greater light interception made possible by larger leaf area results in increased dry matter production. Additionally, the formation of carbohydrates and chlorophyll is encouraged when chemical fertilizers and organic manure is used together, possibly increasing the rate of photosynthesis, the size of the leaves and the leaf area index. These results are consistent with the earlier observations (21, 22). Similarly, application of a combination of inorganic fertiliser and Poultry manure along with biofertilizer application, might have increased the plant's physiological and metabolic processes, allowing for increased growth and nutrient assimilation. It also improves nutrient uptake and utilization efficiency, which results in improved plant growth and a larger leaf area index (23, 24).

The treatment 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) produced the most dry matter per square meter at harvest in both 2022 and 2023 (1180.65 g m^{-2} and 1216.87 g m^{-2}), while the control group (no fertilizer) produced the least amount at harvest (601.29 g m^{-2} and 578.18 g m^{-2}). 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) produced a higher mean dry matter production per square meter at harvest (1198.76 g m^{-2}), while the control group (no fertilizer) produced the lowest mean dry matter production per square meter at harvest (589.74 g m^{-2}) (Table 2).

The combination of inorganic fertilizers and organic manure ensures balanced nutrient availability and produces ideal soil conditions by improving soil structure, nutrient uptake and microbial activity. By increasing the dry weight of the leaves and stems, this promotes greater vegetative growth and the generation of dry matter. Higher levels of photosynthetic activity, light interception, tiller formation and leaf area development are all facilitated by nitrogen, which increases the accumulation of dry matter overall. These results are consistent with earlier studies (25).

Table 1. Impact of INM on the wheat plant height and leaf area index

Treatments	Plant height (cm)			LAI 90 DAS		
	2022	2023	Pooled	2022	2023	Pooled
T1-Absolute control	64.65	63.12	63.89	2.77	2.62	2.70
T2-100 % RDF (120:60:40)	78.78	79.09	78.94	3.80	3.87	3.84
T3-100 % RDF + Azotobacter + PSB +KMB + ZnSB	82.50	83.98	83.24	4.23	4.29	4.26
T4-100 % RDF + NPK Consortia	79.05	80.01	79.53	3.82	3.88	3.85
T5-75 % RDF + 25 % N through Vermicompost (2 t/ha)	79.07	80.29	79.68	3.89	3.97	3.93
T6-75 % RDF + 25 % N through Poultry manure (1 t/ha)	80.05	81.19	80.62	3.97	4.04	4.01
T7-75 % RDF + VC @ 2 t/ha + Azotobacter + PSB +KMB + ZnSB	88.50	90.02	89.26	4.49	4.56	4.53
T8-75 % RDF + VC @ 2 t/ha + NPK Consortia	80.79	82.01	81.40	4.03	4.13	4.08
T9-75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	97.50	99.01	98.26	4.68	4.75	4.72
T10-75 % RDF + PM @ 1 t/ha + NPK Consortia	81.08	82.09	81.59	4.11	4.17	4.14
T11-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	86.06	87.55	86.81	4.34	4.41	4.38
T12-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + NPK Consortia	81.50	82.73	82.12	4.16	4.23	4.20
SEm±	**2.93**	**2.97**	**2.95**	**0.14**	**0.15**	**0.15**
CD (P= 0.05)	**8.59**	**8.70**	**8.65**	**0.41**	**0.43**	**0.45**

Pooled data indicate average of the 2022 and 2023 years.

Table 2. Effect of INM on CGR (Crop growth rate), RGR (Relative growth rate) and dry weight (m^{-2}) of wheat

Treatments	CGR g m^{-2} day^{-1} (60-90 DAS)			RGR mg g^{-1} day^{-1} (60-90 DAS)			Dry matter accumulation (g m^{-2}) at harvest		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T1-Absolute control	6.14	6.19	6.16	14.08	14.75	14.41	601.29	578.18	589.74
T2-100 % RDF (120:60:40)	12.11	12.07	12.09	21.92	21.59	21.75	873.44	875.33	874.39
T3-100 % RDF + Azotobacter + PSB +KMB + ZnSB	13.25	13.55	13.40	21.83	21.97	21.90	960.35	980.20	970.28
T4-100 % RDF + NPK Consortia	12.83	12.90	12.86	21.11	20.89	21.00	903.12	918.63	910.88
T5-75 % RDF + 25 % N through Vermicompost (2 t/ha)	12.87	13.02	12.94	22.31	22.33	22.32	912.76	928.03	920.40
T6-75 % RDF + 25 % N through Poultry manure (1 t/ha)	12.87	13.04	12.95	22.08	22.08	22.08	920.20	937.29	928.75
T7-75 % RDF + VC @ 2 t/ha + Azotobacter + PSB +KMB + ZnSB	14.07	14.28	14.17	21.04	20.95	20.99	1056.78	1081.53	1069.16
T8-75 % RDF + VC @ 2 t/ha + NPK Consortia	12.90	13.09	12.99	21.92	21.94	21.93	928.20	945.42	936.81
T9-75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	15.91	16.11	16.01	22.56	22.37	22.46	1180.65	1216.87	1198.76
T10-75 % RDF + PM @ 1 t/ha + NPK Consortia	13.04	13.16	13.10	21.99	21.91	21.95	936.54	951.15	943.85
T11-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	13.94	14.09	14.02	21.92	21.95	21.93	1015.36	1037.76	1026.56
T12-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + NPK Consortia	13.07	13.20	13.14	21.79	21.77	21.78	945.03	957.76	951.40
SEm±	**0.47**	**0.49**	**0.48**	**0.76**	**0.79**	**0.78**	**33.95**	**34.57**	**34.26**
CD (P= 0.05)	**1.37**	**1.39**	**1.38**	**2.24**	**2.29**	**2.27**	**99.55**	**101.36**	**100.46**

Impact of integrated nutrition management on wheat yield and yield characteristics: The combination of 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) (302 and 312) produced the most spikes per square meter in both 2022 and 2023. The control (no fertilizer) had the fewest tillers per square meter (175 and 171). 75 percent RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) produced the highest number of tillers per square meter (pooled) at harvest (307), while control (no fertilizer) produced the lowest number of tillers per square meter (173).

This might be explained by the increased nutrient availability that PM and inorganic fertilizer offer, as well as by PM's slow nitrogen mineralization and microbial stimulation. These results are consistent with those found in related research (26, 27). Furthermore, the growth and development of wheat tillers was encouraged by the combination of artificial fertilizers and organic manure, which led to more spikes per hill (28).

In comparison to other treatments spike length (10.49 cm, 10.53 cm and 10.51 cm), test weight (40.10 g, 40.20 g and 40.15 g) and number of grains per spike (46.01, 47.02 and 46.52) was higher in 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZSB (T-9) in both years (2022 and 2023) as well as mean. The increased enzymatic activity that results in the production and movement of photosynthates may be the cause of this impact. The spike length, test weight and number of grains per spike may then rise as a result (28), as shown in Table 3.

Grain yield is significantly impacted by the application of integrated nutrient management techniques (Fig. 1). The combination of 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) produced the highest grain yield (5.29 t ha^{-1}, 5.49 t ha^{-1} and 5.39 t ha^{-1}) in both years (2022 and 2023), followed by 75 % RDF + VC @ 2 t/ha + Azotobacter + PSB + KMB + ZSB (T7) (4.80 t ha^{-1}, 4.96 t ha^{-1} and 4.88 t ha^{-1}). The control (no fertilizer) had the lowest grain yield (2.57 t ha^{-1}, 2.38 t ha^{-1} and 2.47 t ha^{-1}).

Table 3. Effect of INM on number of spike (m^{-2}), spike length, number of grains per spike and spike weight of wheat

Integrated nutrient management practices	No. of Spike m^{-2}			Spike length (cm)			No. of grains $spike^{-1}$			Test weight (g)		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T1-Absolute control	175	171	173	9.21	9.17	9.19	38.87	38.09	38.48	38.20	38.00	38.10
T2-100 % RDF (120:60:40)	200	205	203	9.59	9.62	9.61	41.71	41.92	41.82	39.10	39.15	39.13
T3-100 % RDF + Azotobacter + PSB	230	235	233	9.93	9.94	9.94	42.89	43.01	42.95	39.68	39.73	39.71
T4-100 % RDF + NPK Consortia	205	211	208	9.63	9.66	9.65	41.76	41.92	41.84	39.13	39.17	39.15
T5-75 % RDF + 25 % N through Vermicompost (2 t/ha)	207	213	210	9.68	9.70	9.69	41.91	42.05	41.98	39.19	39.23	39.21
T6-75 % RDF + 25 % N through Poultry manure (1 t/ha)	210	216	213	9.73	9.75	9.74	41.98	42.14	42.06	39.28	39.34	39.31
T7-75 % RDF + VC @ 2 t/ha + Azotobacter + PSB +KMB + ZnSB	260	271	266	10.25	10.27	10.26	43.59	43.91	43.75	39.89	39.95	39.92
T8-75 % RDF + VC @ 2 t/ha + NPK Consortia	213	218	216	9.77	9.79	9.78	42.11	42.34	42.23	39.37	39.42	39.40
T9-75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	302	312	307	10.49	10.53	10.51	46.01	47.02	46.52	40.10	40.20	40.15
T10-75 % RDF + PM @ 1 t/ha + NPK Consortia	221	227	224	9.83	9.89	9.86	42.19	42.41	42.30	39.46	39.51	39.49
T11-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	245	252	249	9.99	10.04	10.02	43.03	43.29	43.16	39.73	39.77	39.75
T12-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + NPK Consortia	227	233	230	9.89	9.93	9.91	42.77	43.97	43.37	39.59	39.64	39.62
SEm±	**8.15**	**8.38**	**8.26**	**0.35**	**0.35**	**0.35**	**1.51**	**1.52**	**1.52**	**1.40**	**1.40**	**1.40**
CD (P= 0.05)	**23.90**	**24.56**	**24.23**	**NS**	**NS**	**NS**	**4.43**	**4.47**	**4.45**	**NS**	**NS**	**NS**

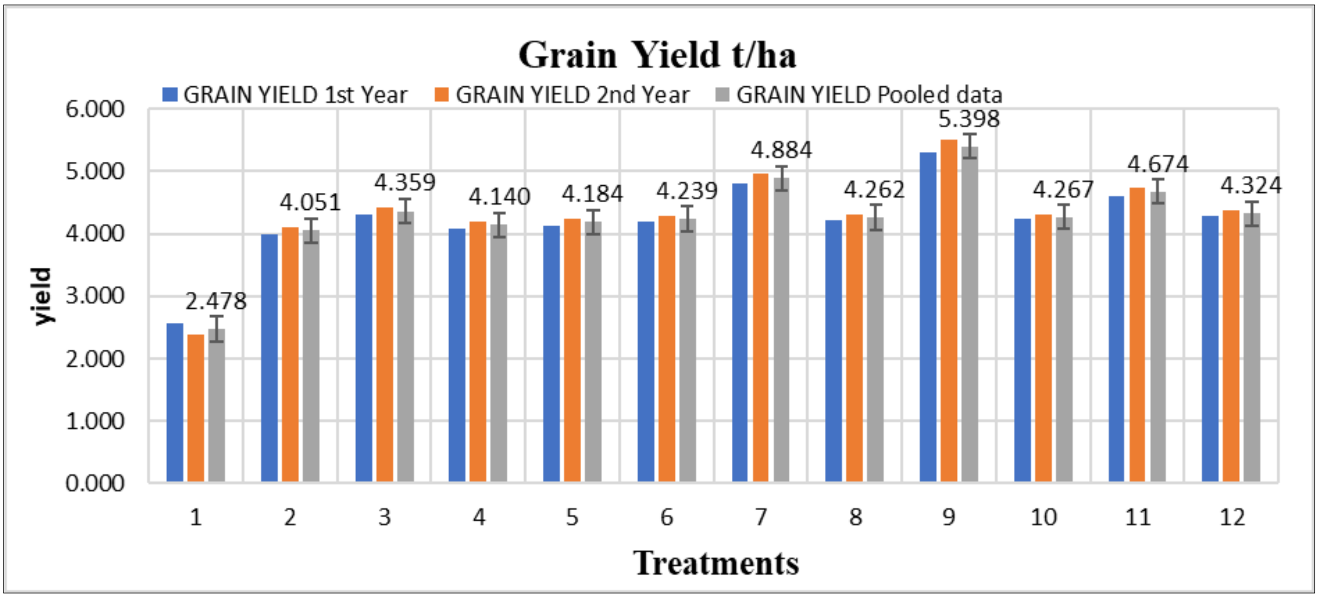

Fig. 1. Effect of integrated nutrient management on grain yield of wheat.

As shown in Fig. 2, the highest biological yield among the various treatments was recorded with 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZSB (T-9) (12.60 t ha^{-1}, 13.01 t ha^{-1} and 12.81 t ha^{-1}) in both the years 2022 and 2023 as well as mean. This was followed by 75 % RDF + VC @ 2 t/ha + Azotobacter + PSB +KMB + ZSB (T7) (11.43 t ha^{-1}, 11.83 t ha^{-1} and 11.63 t ha^{-1}). The control (no fertilizer) had the lowest biological yield (6.51 t ha^{-1}, 6.25 t ha^{-1} ha and 6.38 t ha^{-1}). Maximum biomass production was achieved by the optimal combination of PM and conventional fertilizers.

The application of 75 % RDF + PM @ 1 t/ha + Azotobacter + PSB + KMB + ZSB (T-9) produced the highest harvest index among the various treatments (42.02 %, 42.26 % and 42.14 %) during both two years as well as the mean. The control (no fertilizer) produced the lowest harvest index (39.52 %, 38.13 % and 38.82 %), but there was no discernible effect on the harvest index, as shown in Fig. 3.

Because of their high nutrient content and low C/N ratio, which permits faster mineralisation than other organic materials, organic fertilisers (FYM) are very successful at increasing crop yields. Higher nutrient availability and absorption are supported by this progressive nutrient release, which improves photosynthate accumulation and translocation and, eventually, increases grain yield. By gradually increasing soil fertility and nutrient delivery throughout the season, NPK and PM together further increase grain yield by promoting higher leaf expansion, improved photosynthesis and effective photosynthetic translocation to the grain. Higher leaf area expansion and improved photosynthesis, which results in more tillers, are associated with increased straw yield when integrated nutrition management (INM) treatments are used. Better dry matter production and enhanced growth characteristics were the outcomes of this. More economic output is indicated by a higher harvest index, which was primarily brought about by adequate nutrient availability during the stages of reproduction, spike initiation and grain filling as well as effective photosynthetic translocation to the grains. These results align with the findings of earlier studies (28-30), They found that combining chemical and organic fertilisers significantly improved biological and wheat grain yields.

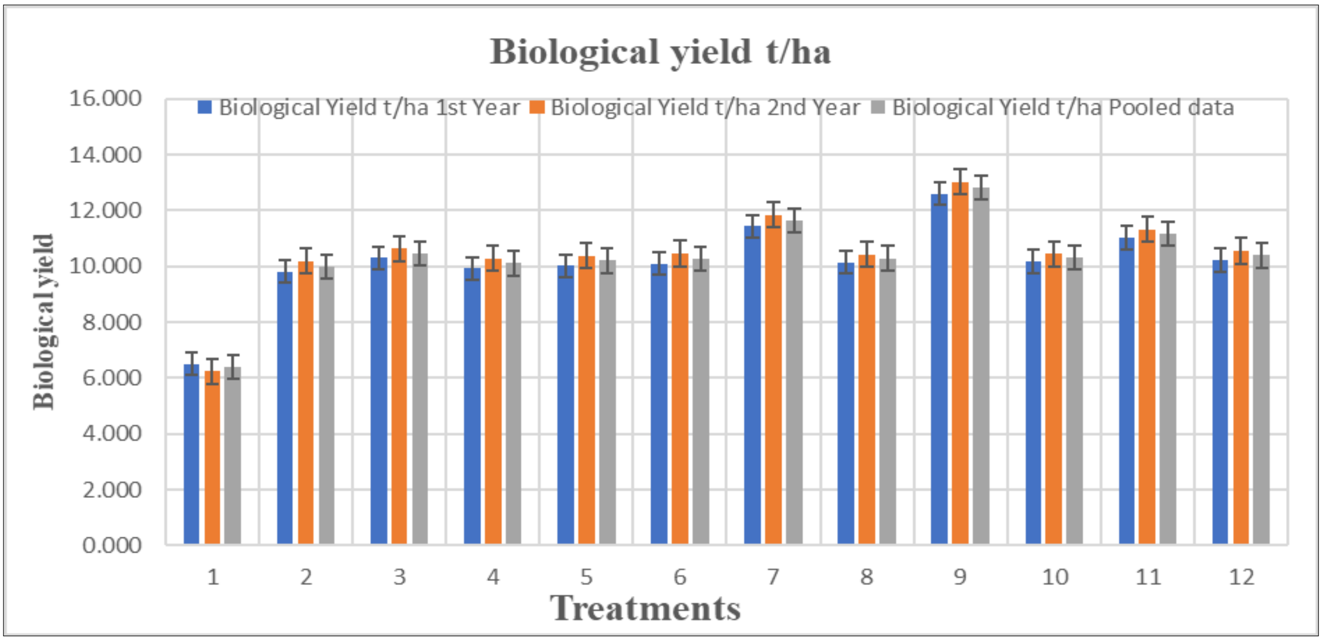

Fig. 2. Effect of integrated nutrient management on biological yield of wheat.

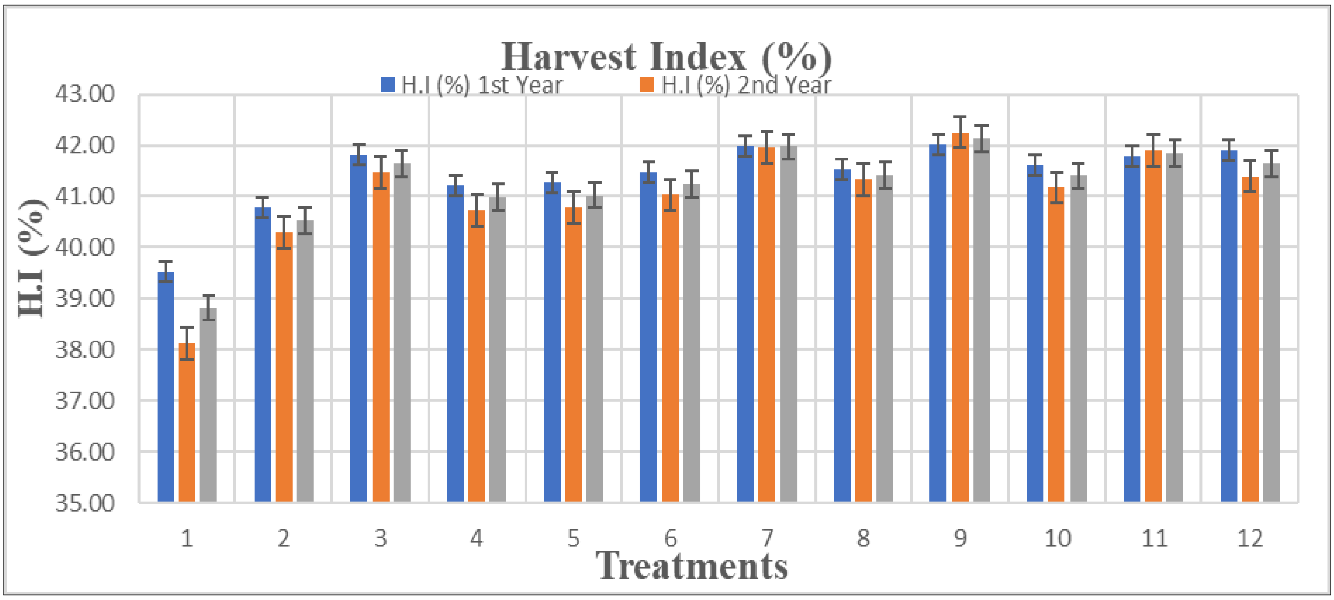

Fig. 3. Effect of integrated nutrient management on harvest index of wheat.

Impact of integrated nutrient management on soil biochemical properties: After two years of cropping, the soil's chemical characteristics (Table 4) revealed a minor rise in pH and organic carbon content relative to the starting values, with the exception of the control plot's organic carbon content, which was found to be lower than the starting values. When compared to other treatments, the application of PM alone or in conjunction with inorganic fertilizers increased the amount of organic carbon in the soil after harvest. A similar pattern was also seen in the pH of the soil.

In comparison to the initial levels, the fungal population decreased after two years of cropping, but the bacterial and actinomycetes populations grew (Table 4). In comparison to INM and inorganic methods, organic management in wheat enhanced the establishment of microbial colonies more successfully (bacteria 12.25 ×106, actinomycetes 7.36 ×106 and fungi 6.83 ×104 cfu/g soil). This may be because organic inputs have a greater impact on microbial populations and their activities than when paired with inorganic inputs (31).

Study of Correlation

Grain yield

The study revealed that trait Grain yield had a positive and significant relationship with dry matter accumulation (0.996), Leaf area index (0.984), Plant height (0.984), CGR (0.983), Test weight (0.971), No. of grain spike^{-1} (0.96), Spike length (0.943) and RGR (0.719) (Fig. 4).

Test weight

The present investigation unveiled that trait Test weight had a positive and significant association with Leaf are index (0.994), dry matter accumulation (0.973), Plant height (0.959), Spike length (0.957), CGR (0.952), No. of grain spike^{-1} (0.948) and RGR (0.678).

Spike length

The traits Plant height (0.976), No. of grain spike^{-1} (0.966), dry matter accumulation (0.963), Test weight (0.957), Leaf area index (0.937) and CGR (0.879) showed a positive and significant association with Spike length. Additionally, a positive correlation with RGR (0.472 NS) was noted, albeit without statistical significance.

Table 4. Impact of INM on soil pH, bacteria, actinomycetes, fungal population and soil organic carbon

Integrated nutrient management practices	Organic carbon (%)	pH	Bacteria (x 10^6 cfu /g soil)	Actinomycetes (x 10^6 cfu /g soil)	Fungi (x 10^4 cfu /g soil)
T1-Absolute control	0.32	8.34	9.96	6.30	5.34
T2-100 % RDF (120:60:40)	0.32	8.39	9.95	6.28	5.29
T3-100 % RDF + Azotobacter + PSB +KMB + ZnSB	0.38	8.01	11.98	7.20	6.70
T4-100 % RDF + NPK Consortia	0.35	8.26	10.59	6.73	6.10
T5-75 % RDF + 25 % N through Vermicompost (2 t/ha)	0.36	8.15	11.26	6.96	6.42
T6-75 % RDF + 25 % N through Poultry manure (1 t/ha)	0.36	8.12	11.47	7.06	6.43
T7-75 % RDF + VC @ 2 t/ha + Azotobacter + PSB +KMB + ZnSB	0.39	7.98	12.22	7.29	6.76
T8-75 % RDF + VC @ 2 t/ha + NPK Consortia	0.37	8.07	11.73	7.07	6.49
T9-75 % RDF + PM @ 1 t/ha + Azotobacter + PSB +KMB + ZnSB	0.39	7.93	12.25	7.36	6.83
T10-75 % RDF + PM @ 1 t/ha + NPK Consortia	0.38	8.04	11.79	7.12	6.54
T11-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + Azotobacter + PSB	0.38	7.99	12.13	7.26	6.74
T12-50 % RDF + VC @ 2 t/ha + PM @ 1 t/ha + NPK Consortia	0.38	8.01	11.93	7.15	6.65
SEm±	**0.01**	**0.29**	**0.41**	**0.25**	**0.23**
CD (P= 0.05)	**0.04**	**NS**	**1.20**	**NS**	**0.67**
Initial	**0.33**	**8.33**	**9.79**	**6.32**	**5.37**

*cfu = Colony forming unit, SEm = Standard error of mean, CD = Critical difference

Variables	Grain yield	Test weight	Spike length	No. of grain spike^{-1}	Leaf are index	Plant height	dry matter	CGR	RGR
Grain yield	1.0000								
Test weight	0.9710	1.0000							
Spike length	0.9430	0.9570	1.0000						
No. of grain spike^{-1}	0.9600	0.9480	0.9660	1.0000					
Leaf are index	0.9840	0.9940	0.9370	0.9380	1.0000				
Plant height	0.9840	0.9590	0.9760	0.9830	0.9580	1.0000			
dry matter	0.9960	0.9730	0.9630	0.9730	0.9790	0.9930	1.0000		
CGR	0.9830	0.9520	0.8790	0.9210	0.9760	0.9420	0.9720	1.0000	
RGR	0.7190	0.6780	0.4720	0.5690	0.7400	0.5940	0.6720	0.8270	1.0000

Fig. 4. Correlation plot between grain yield, test weight, spike length, no. of grain spike^{-1}, leaf area index, plant height, dry matter (m^{-2}) CGR and RGR.

No. of grain spike^{-1}

The study revealed that trait No. of grain spike^{-1} had a positive and significant relationship with Plant height (0.983), dry matter (0.973), Spike length (0.966), Test weight (0.948), Leaf are index (0.938) and CGR (0.921). Additionally, there is a positive but non-significant correlation with RGR (0.569 NS).

Leaf area index

The present investigation unveiled that trait Leaf are index had a positive and significant association with Test weight (0.994), dry matter accumulation (0.979), CGR (0.976), Plant height (0.958), No. of grain spike^{-1} (0.938), Spike length (0.937) and RGR (0.74).

Plant height

The traits dry matter accumulation (0.993), No. of grain spike^{-1} (0.983), Spike length (0.976), Test weight (0.959), Leaf are index (0.958), CGR (0.942) and RGR (0.594) showed a positive and significant association with Plant height.

Dry matter accumulation

The study revealed that trait dry matter accumulation had a positive and significant relationship with Plant height (0.993), Leaf area index (0.979), Test weight (0.973), No. of grain spike^{-1} (0.973), CGR (0.972), Spike length (0.963) and RGR (0.672).

CGR

The present investigation unveiled that trait CGR had a positive and significant association with Leaf are index (0.976), dry matter accumulation (0.972), Test weight (0.952), Plant height (0.942), No. of grain spike^{-1} (0.921), Spike length (0.879) and RGR (0.827).

RGR

The traits CGR (0.827), Leaf area index (0.74), Test weight (0.678), dry matter accumulation (0.672) and Plant height (0.594) showed a positive and significant association with RGR. Additionally, a positive correlation with No. of grain spike^{-1} (0.569 NS) and Spike length (0.472 NS) was noted, albeit without statistical significance.

Conclusion

The results of the two-year field experiment clearly demonstrated that the integrated nutrient management practice involving 75 % of the recommended dose of fertilizers (RDF) along with the application of 1 t/ha poultry manure (PM) and biofertilizers including *Azotobacter*, phosphate-solubilizing bacteria (PSB), potassium-mobilizing bacteria (KMB) and zinc-solubilizing bacteria (ZSB) significantly enhanced wheat yield and improved soil health indicators. This integrated approach led to substantial improvements in plant growth attributes, nutrient uptake and grain and straw yield compared to conventional fertilizer use. Additionally, the inclusion of poultry manure and microbial inoculants contributed to improved soil organic carbon content, microbial biomass and nutrient availability, indicating better soil fertility and biological activity. Thus, the combination of organic, inorganic and biological sources of nutrients provides a balanced and sustainable strategy for wheat cultivation that reduces chemical fertilizer dependency while improving agroecosystem resilience.

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Authors' contributions

All the authors contributed to the above work, starting from designing the experiment, collecting data, assisting with statistical analysis, interpretation of results and manuscript preparation. All the authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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