Journal of Applied and Natural Science
16(3), 976 - 986 (2024)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Research Article

Optimization of integrated nutrient management for enhancing growth and yield of wheat (*Triticum aestivum)* in sandy loam soil

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Article Info
https://doi.org/10.31018/jans.v16i3.5660
Received: April 21, 2024
Revised: June 30, 2024
Accepted: July 06, 2024

How to Cite

Singh, W. *et al.* (2024). Optimization of integrated nutrient management for enhancing growth and yield of wheat (*Triticum aestivum)* in sandy loam soil. *Journal of Applied and Natural Science*, 16(3), 976 - 986. https://doi.org/10.31018/jans.v16i3.5660

Abstract

Wheat (*Triticum aestivum*) is a globally significant cereal crop with vital roles in human civilization and the agricultural revolution. The present study aimed to investigate the impact of Integrated Nutrient Management (INM) strategies on vegetative growth and yield parameters such as plant height, spike length, grains per spike, spike m^{-2}, grain yield, biological yield, straw yield leaf area index, harvest index, and soil nutrient availability of wheat genotype PBW 590 (*Triticum aestivum*). The experiment was set up in randomised block design (RBD) with nine treatments in triplicates using different ratios of NPK, farm yard manure, vermicompost etc. The results indicated significant variations in plant height among the treatments (T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8 and T_9) with the maximum (95.1 cm) in T_4 (70% recommended dose of fertilizer + 2.5% *Azospirillum* + 2.5% phosphate solubilizing bacteria + 20% Farm yard manure + 5% Vermicompost), surpassing the recommended dose of fertilizer by 6.17%. Leaf Area Index positively responded to INM treatments, with T_4 displaying the highest LAI (4.55), suggesting enhanced photosynthetic efficiency. Harvest Index (HI) indicated resource allocation towards edible yield, with T_4 exhibiting the highest HI (50.7%) which was 34% higher than RDF. T_4 consistently showed positive effects on the parameters, such as spike length (14.1 cm) and grains per spike (33), demonstrating variations among the treatments. Nutrient availability (N, P, and K) in the soil significantly improved under INM treatments, particularly T_4, showcasing the potential for nutrient management in enhancing wheat growth and improving soil health.

Keywords: Biological yield, Harvest Index, Integrated Nutrient Management, Nutrient availability, Wheat

INTRODUCTION

Cereals are the major energy and nutritional source for the global population especially living in rural areas (Sharma *et al.*, 2024a, b). Among the cereals, Wheat *(Triticum aestivum)*, is a widely cultivated cereal crop for the development of human civilization globally (Chatterjee *et al.*, 2021; Chen *et al.*, 2021; Zulfiqar *et al.*, 2023). Wheat ranks 1st in production and area of cultivation, followed by corn, rice and barley (Sharma *et al.*, 2023; Philippot *et al.*, 2024). Globally, the wheat cultivated area in 2022 was 219.15 m/ha, with a production of 0.8 billion metric tonnes (FAOSTAT, 2022). It has played a crucial part in the shift from hunter-gatherer societies to settled agriculture, contributing to notable progress in human civilization (Yan *et al.*, 2019). Wheat and wheat-based products are essential components of a balanced diet for billions of people worldwide as they are abundant in carbohydrates, especially starch, serving as a significant energy source (Meena *et al.*, 2013; Meena *et al.*, 2021). Additionally, it encompasses proteins, dietary fibre, vitamins (B- complex vitamins), and minerals (Iron, magnesium, phosphorus, and zinc (Fazily *et al.*, 2021; Gogoi *et al.*, 2021;

Jat *et al.*, 2022; Kandeler *et al.*, 2024).

Excessive use of synthetic fertilizer in the soil for the past 50 years resulted in losing the soil's availability of nutrients (macronutrients and micronutrients) (Chondie and Y.G, 2015; Nath *et al.*, 2023). Excessive use of synthetic fertilizers in the soil not only results in poor grain quality, crop disease, and insect susceptibility in the wheat crop but also degrades the environment (Nehra *et al.*, 2001; Alori *et al.*, 2017; Liu *et al.*, 2020; Zhang *et al.*, 2021; Liu *et al.*, 2021; Yang *et al.*, 2022). Low nutrient use efficiency (NUE), might significantly influence agricultural practices to maximize output and reduce soil degradation (Calders *et al.*, 2018; Broberg *et al.*, 2021; Jat *et al.*, 2022).

The current scenario of modern agriculture also optimizes soil fertility, production, and productivity for sustainable agriculture (Yan *et al.*, 2016a; Darjee *et al.*, 2023; Li *et al.*, 2024). These might be increased by using bio-fertilizers such as Azotobactor, PSB (phosphate solubilizing bacteria) and *Azospirillum* in contrast to inorganic fertilisers (Bastakoti *et al.*, 2017; Sarwar *et al.*, 2023). Integrated Nutrient Management (INM) is a better initiative that can significantly impact the effectiveness of fertiliser use (Saito *et al.*, 2021; Sarvar *et al.*, 2023; Sarwar *et al.*, 2023; Hütsch *et al.*, 2023). The nutrient availability is slow when applied through INM but enhances the production (Devi *et al.*, 2021; Dhaliwal *et al.*, 2021; Ahmad *et al.*, 2024). So, the present study was designed to reveal the most suitable combination for replenishing soil nutrients through INM and its effects on wheat growth and yield parameters.

MATERIALS AND METHODS

Study site and experimental setup

Two years field experiment was carried out at the farm located at 28.688027 N latitude and 76.636683 E longitude in the Dujana village, Jhajjar, Haryana (India) during two consecutive Rabi seasons of 2021-22 and 2022-23. The experiment was carried out using wheat genotype PBW 590 (Certified seeds were bought from ICAR, Karnal) in a triplicated randomized block design (RBD) with 9 treatments. The study was conducted under farm conditions using block size of 3.0 × 2.0 m (net). The sowing was done using the seed drilling method in lines 20 cm apart with a 100kg/ha seed rate.

Meteorology

The data for weekly average atmospheric temperature, relative humidity, rainfall, and wind speed at the experimental site for the study period was taken from the Indian Meteorological Department depicted in Fig. 2 (IMD, 2022, 2023). During the cropping season from the 1st week of December to the second week of April (2021-23), the average relative humidity was 75.53%, with a maximum of (96.7%) in the 2nd week of February and a minimum of (34.76%) in the 4th week of March in both seasons. The total rainfall during the cropping season was (33.86 mm) and maximum rainfall was recorded in the 3rd week of March (7.5 mm). The hottest week (30.52 °C) was recorded in 4th week of March and the coldest (9.1 °C) was in the 2nd week of January. The highest wind speed recorded was (26.33 km/hr) in the 2nd week of March, and the minimum was (5.3 km/hr) during cropping season in the 1st week of December.

Soil sampling and analysis

Before sowing the seeds, five soil samples were taken from different locations of the experimental field from 0-20 cm depths and were evenly mixed, dried, crushed, and passed through a 2 mm sieve to prepare a composite sample. A phytochemical analysis of the soil was done before sowing and after harvesting the crop. The texture of the soil was analyzed using the International pipette method (Piper, 1966). The results revealed that the soil was dominated by sandy parts followed by silt and clay, as shown in Fig.2.

A physiological analysis of the soil was done before sowing (Table 1) and after harvesting the crop. Soil pH was measured using a pH glass electrode meter (PHS-3E, Shanghai, China) in the soil-to-water ratio (weight/volume) was 1:5 (Jackson, 1967). Organic carbon was determined using the wet digestion method (Walkley and Black, 1934). The total nitrogen (N) content was measured using the Kjeldahl method using a 2300 FOSSTM instrument (Bremner and Mulvaney, 1983). The Olsen method was used for phosphorus analysis in soil (Olsen *et al.*, 1954). Potassium was determined using a Flame Photometer (Richards, 1954).

Treatments

A total of 9 treatments were prepared using different ratios of inorganic fertilizers, farmyard manure, vermicompost and bio-fertilizers. FYM was prepared in the field before the experimental setup using cattle dung, urine, and rice crop residue. Vermicompost, PSB (Phosphate solubilizing bacteria) and *Azotobactor* were bought from the IFFCO bazaar. Vermicompost and FYM were applied at the tillage time. NPK fertilizers, PSB and *Azotobacter* were applied at 40 DAS and 80 DAS. Treatments were designed using recommended doses of 80, 40, and 20 kg/ha for N, P and K fertilizers, respectively (https://agritech.tnau.ac.in/agriculture/agri_nutrientmgt_wheat.html). Treatments for study were- T_1: 100% RDF (Recommended Dose of NPK Fertilizers), T_2: 90% RDF + 5% *Azospirillum* + 5% PSB, T_3: 80% RDF + 5% *Azospirillum* + 5% PSB + 10% FYM (Farm yard manure), T_4: 70% RDF + 2.5% *Azospirillum* + 2.5% PSB + 20% FYM + 5% Vermicompost, T_5: 60% RDF + 5% *Azospirillum* + 5% PSB + 30% FYM, T_6: 80% RDF + 5% *Azospirillum* + 5% PSB + 10% Vermicompost, T_7: 70 % RDF + 30% Vermicom-

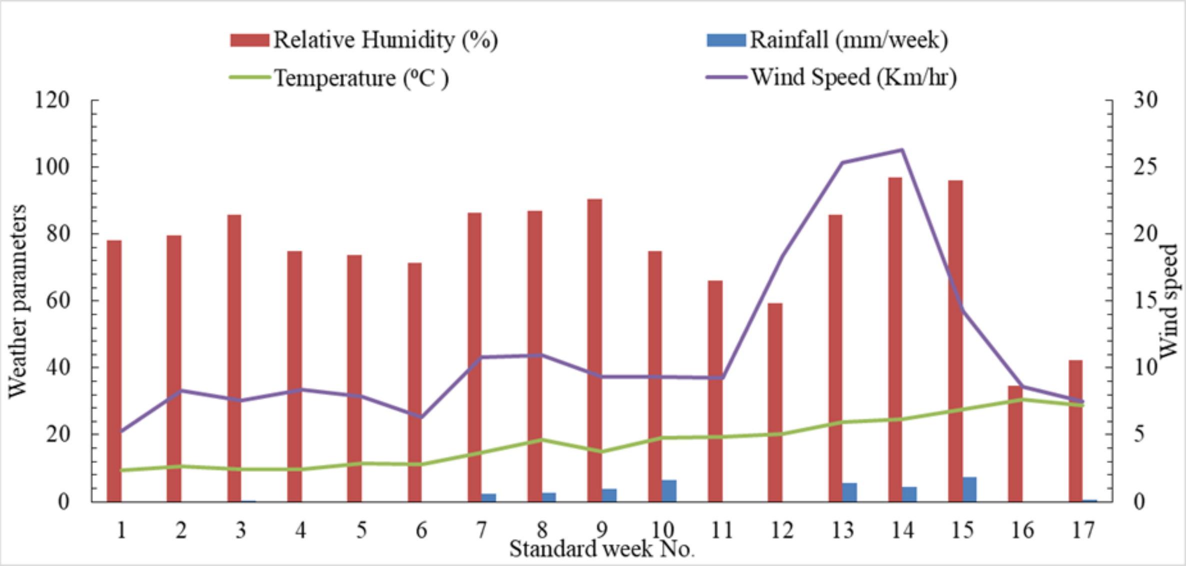

Fig. 1. Mean weekly average meteorological condition during the crop growing season (IMD, 2022 & 2023).

post, T_8: 60% RDF + 40% Vermicompost, T_9: 50% RDF + 25% FYM + 25% Vermicompost.

Growth and yield attributes

The average plant's height was determined at 30, 60 and 90 days after sowing (DAS) and maturity by randomly selecting five different plants from each block, and their heights were measured in centimetres from the base of the plant to its longest leaf tip and averaged (Zadoks *et al.*, 1974). Similarly, spike length, number of spikes, and grains per spike were determined from a representative sample of five plants from each block and average values were recorded (Zadoks *et al.*, 1974). The grain yield for each block was recorded in kg/ha by separating, drying, and weighing the cobs. Similarly, after separating the grains, the remaining part of the plant was weighed and straw yield was recorded in kg/ha. LAI for each block was calculated at 30, 60 and 90 DAS. Maturity was calculated using the ratio of a plant's total leaf area to the ground area covered by a plant (Pierce & Running, 1988).

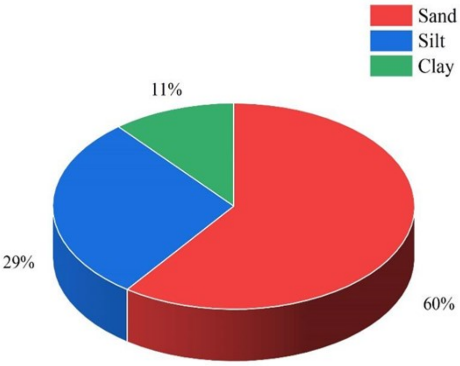

Fig. 2. Soil texture of study site (Dujana village, Haryana).

$$LAI = \frac{Total\ Leaf\ Area\ of\ a\ Plant}{Ground\ area\ covered\ by\ a\ plant} \tag{1}$$

The harvest index (HI) was calculated by ratio of grain yield to biological yield as follows (Pierce & Running, 1988):

$$Harvest\ Index\ (\%) = \frac{Grain\ yield}{Biological\ yield} \times 100 \tag{2}$$

Statistical analysis

The results were presented using the average values of three replicates ± SE and were statistically evaluated using Analysis of variance (ANOVA). Tukey's HSD post hoc test was performed to evaluate the significant differences between treatments at a 5% level of significance ($P<0.05$). The statistical tool “Origin Pro 2024” was used to plot the graph and perform statistical analyses.

RESULTS AND DISCUSSION

Physiochemical properties of harvested soil

The analysis of physiochemical parameters of harvested soil indicated that the pH values ranged from 7.10 to 8.7 across different treatments, indicating significant influence from various treatment conditions.

The highest pH (8.6) was observed in T_6, as shown in Fig. 3 (a), while the lowest (7.1) was noted in T_4, reflecting a nearly neutral state. The pH value of soil of T_4 was found to be significantly different ($p < 0.05$) from all other treatments. pH influences the avai lability of essential nutrients to plants and its value in soil should be between 6.5-7.5 (Mahmud *et al.*,2021). Similarly, soil electrical conductivity (EC) was also impacted by diverse treatments. High EC levels indicate high salt content in the soil, which can be harmful to plants. Salinity affects water uptake by plants, leading to osmotic

Table 1. Physiochemical analysis of soil before applying the treatments

pH	EC (dSm^{-1})	OC (%)	N (Kg/ha)	P (Kg/ha)	K (Kg/ha)
8.2±0.06	0.52±0.005	0.21±0.112	160.4±0.305	12.3±0.173	137.5±0.550

stress and reduced growth (Su *et al.*, 2021). The EC value (0.61 dSm^{-1}) was observed in T_4, whereas the lowest EC (0.22 dSm^{-1}) was found in T_9 as shown in Fig. 3(b). The desirable value of EC in soil is less than 4 dSm^{-1} (Mahmud *et al.*, 2021).

The incorporation of integrated fertilization practices demonstrated a clear and positive impact on enhancing the organic carbon pool within the soil matrix. OC in the soil is a measurable component that remains in the soil after the partial decomposition of any living organism (Mahmud *et al.*, 2021; Jat *et al.*, 2022). The effects of different treatments on available organic carbon in the soil are shown in Fig. 3 (c). The most notable improvement was observed in T_4 with organic content of 0.6%, which is 33.3% higher than RDF, followed by T_5, T_6, and T_9 with OC content of 0.4%. The range of OC should be in the range of 0.55%-2.55% for plant growth (Mahmud *et al.*, 2021). The results of the current study were consistent with the studies of Agegnehu *et al.* (2014) and Mahmud *et al.* (2021) on wheat crop in sandy loam soil.

The available nitrogen in the soil varied little among the different treatments. The maximum concentration (168.90 Kg/ha) of nitrogen was observed higher with the T_4, which was statically differenent ($p < 0.05$) from T_2 and T_5 as shown in Fig. 3 (d). The range of available N in soil should be 120 kg/ha to 170 g/ha for plant growth (Jat *et al.*, 2022). The variation in treatments may be attributed to an increase in the activity of the non-symbiotic nitrogen-fixing bacteria due to the use of biofertilizers and vermicompost. Nitrogen availability in soil is a key factor in determining the health of soil and the productivity of plants on wheat plant (Dai *et al.*, 2015). Similar alterations of physicochemical parameters were also observed by Mahmud *et al.* (2021) and Jat *et al.* (2022) for wheat crop.

Available P is one of the macronutrients of soil required in the range of 11kg/ha to 22kg/ha for plant growth (Mahmud *et al.*, 2021).The concentration of available phosphorous was found to be highest in soil of T_4 (22.7 kg/ha), which was significantly different ($p < 0.05$) from all other treatments, as shown in Fig. 3 (e). Available phosphorous in the soil of T_2 and T_4 was significantly different ($p < 0.05$) from each other and from other treatments also. This may be attributed to the increase in the growth of phosphate-solubilizing bacteria.

Potassium (K) is one of the essential macronutrients that plants need for proper growth and development. It plays an important role in various physiological processes within plants, including photosynthesis, water regulation, enzyme activation, and overall plant health (Bader *et al.*, 2021). The desired range for the available K in the soil is 110kg/ha to 280 kg/ha (Bader *et al.*, 2021). The highest amount of available K in harvested soil was found in T_4 (148.9 kg/ha) and the lowest was in T_3 (133.9 kg/ha), as shown in Fig. 4(f). Available K harvested soil of T_1, T_2, T_3 and T_4 was found to be significantly different ($p < 0.05$) from each other and from other treatments also.

Growth parameters

Plant height

The height of the plants gradually increased with time in all the treatments and reached its peak at physiological maturity, as shown in Fig. 4. The pace of growth varied at different stages, with noticeable differences due to different treatment doses, except at the 30 DAS stage. The effects of different treatments became evident after 60 DAS and persisted till maturity.

The maximum height (94.6) cm was recorded at the harvesting stage, with T_4, which was significantly difference ($p < 0.05$) from the RDF. This may be attributed to the higher concentrations of bio-stimulant combined with farm yard manure and vermicompost doses, which boosted the ability of the wheat plants to supply nutrients, which led to faster growth rates. Due to an ideal proportion of biofertilizers and manure, the maximum plant height can promote stem elongation, influencing plant height to achieve desired characteristics. Minimum height (71.2 cm) was recorded in T_7, indicating that *Azospirillum* and PSB played a significant role in the growth of plants by enhancing the available nitrogen and phosphorus in the soil. The exclusive use of vermicompost, without including *Azospirillum* and PSB, might not be as effective in promoting wheat plant height (Bader *et al.*, 2021). In the present study, taller plants observed in the experimental blocks received a combination of vermicompost, biofertilizers, and chemical fertilizers. The optimal proportion of these inputs appeared to promote stem elongation, influencing plant height positively and leading to faster growth rates (Die *et al.*, 2016).

Spike length

The effect of different treatments on spike length is shown in Fig. 5. The longest spike length (12.7) cm, was observed in T_4 which was found significantly different (($p < 0.05$) from T_1, T_6, T_7 and T_9. The spike length of T_1 was found to be significantly different (($p < 0.05$) from T_4, T_5 and T_8. Uses of biofertilizer PSB along with FYM and *Azospirillum* with 70% RDF enhanced the microbial ecology of the soil. Rhizobacteria (PGPR)

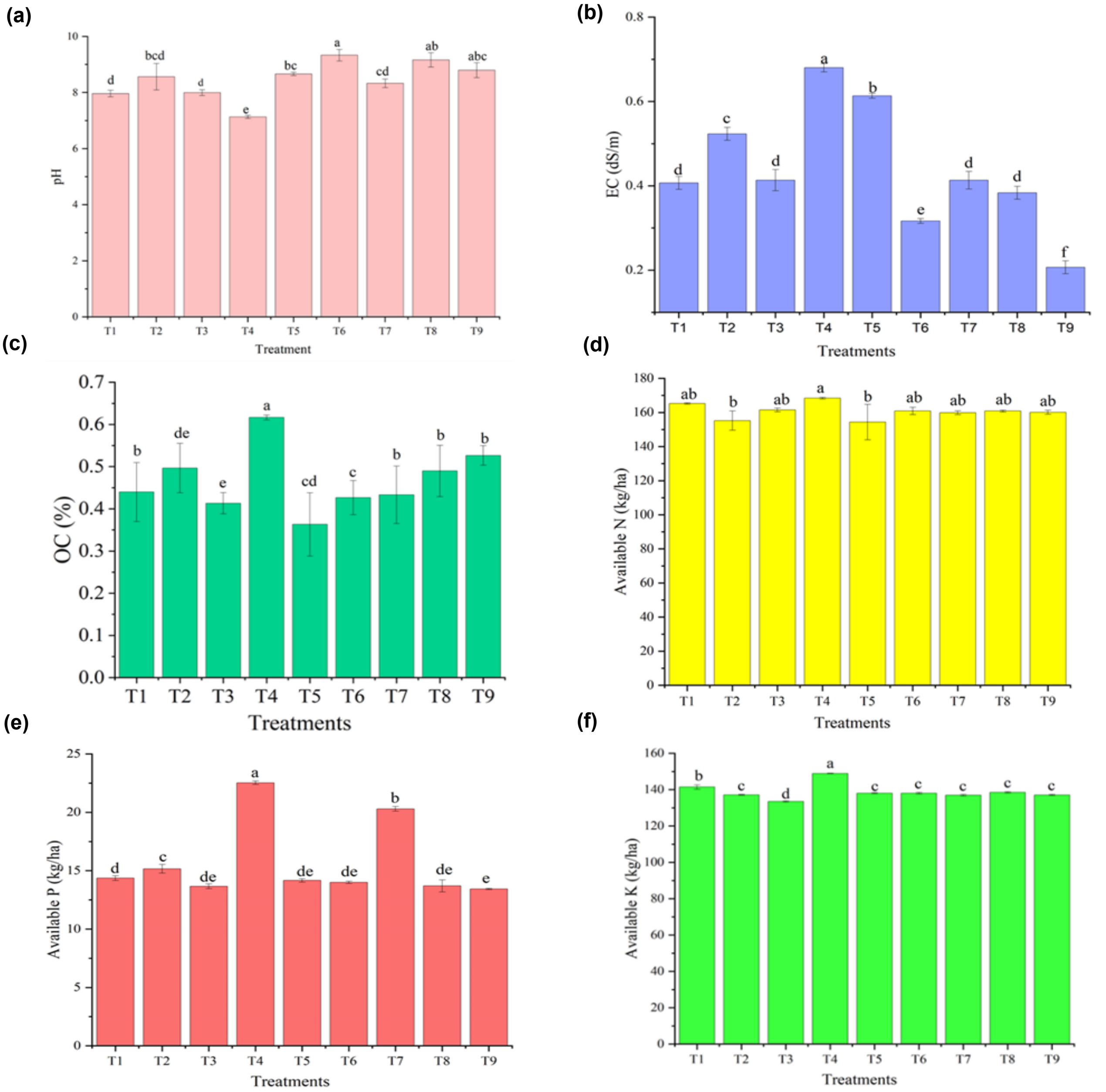

Fig. 3. *Showing the relationship between physiochemical parameters of soil after harvesting for different treatments, where lowercase letters represent the significance difference evaluated by Tukey's post hoc test (p < 0.05)*

plays a major role in nitrogen fixation and produces plant hormone auxin, which promotes cell growth and elongation of the plant (Arya *et al.*, 2017). Broberg *et al.* (2021) observed similar results of increased microbial activities in the soil by the use of biofertilizer along with FYM . In another study, it was reported that an excess amount of biofertilizer in addition to recommended amount enhances plant nutrient absorption capacity, decreasing the plant's vegetative growth (Chatterjee *et al.*, 2021).

Leaf Area Index (LAI)

Leaf area index was calculated for all the treatments at all the plant stages in Fig. 6. LAI progressively increased up to 60 DAS and then showed a decreasing trend. Among all the nutrient management approaches, minimum value of LAI was recorded in T_9 (2.0) and the highest value was observed in T_4 (4.1) at 90 DAS. The LAI for T_4 was significantly different ($p < 0.05$) from the LAI for all other treatments at 90 DAS. This might be associated with the enhanced availability of nitrogen and other nutrients in the T_4. Li et al (2011) and Zhang *et al.* (2021) have also reported enhancement in wheat leaf area by appropriate nitrogen application.

In comparison to the RDF, T_4 produces significantly higher LAI of 56% and 41.37% at 60 DAS and 90 DAS, respectively, as shown in Fig. 6. This indicates that integrated uses of nutrients make a dynamic ecosystem that was responsible for higher leaf area in wheat. Campoy *et al.*, 2020 and Qin *et al.*, 2021 have also

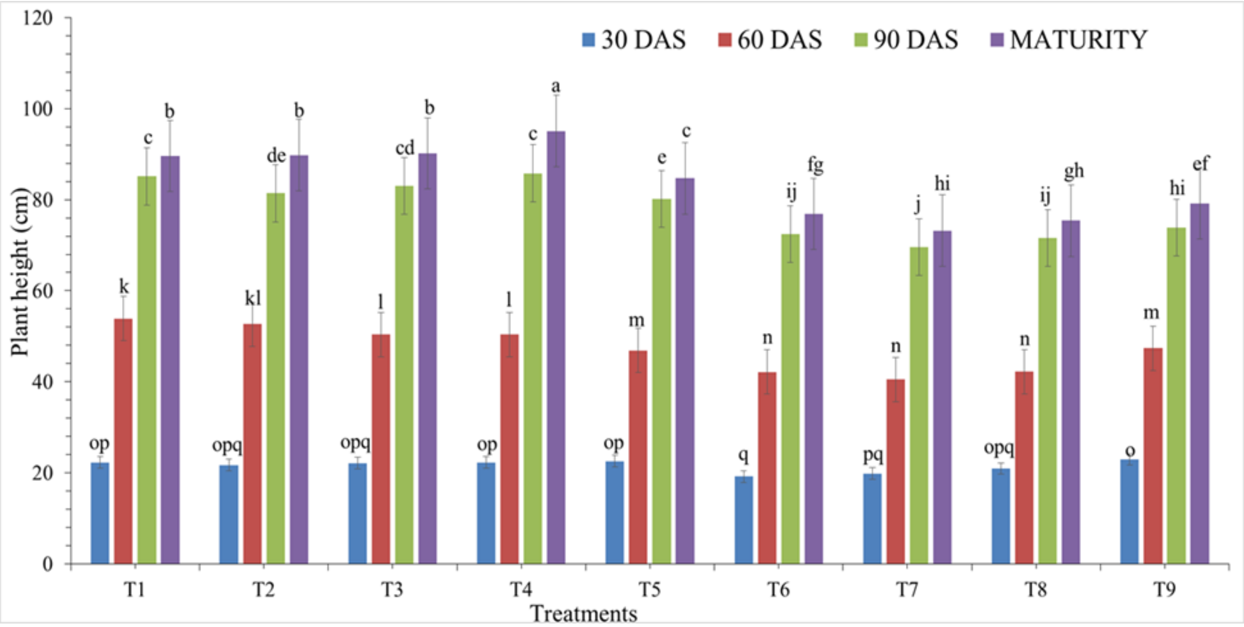

Fig. 4. *Plant height (cm) of wheat during 2022-2023 at successive growth stages affected by different INM treatments where lowercase letters represent the significance difference as evaluated by Tukey's post hoc test ($p < 0.05$)*

reported higher LAI in biofertilizers and vermicompost applications in wheat.

Yield parameters

Spikes density and grains per spike

In this study, treatment T_4 recorded the highest spike density of (475.4) spikes per square meter, while T_9 had the lowest (305.5) spikes per square meter as shown in Fig. 7(a). Spike density (spikes per square meter) is a valuable agricultural metric, with a higher density generally indicating greater yield potential (Ruiz *et al.*, 2023). Spike density for all the treatments were found to be significantly different ($p < 0.05$) from each other.

The maximum number of grains per spike were reported in T_4 (28.6) and minimum was in T_9 (23.6) as shown in Fig. 7(b). Grains per spike for T_1 were found significantly different ($p < 0.05$) from T_4, T_5 and T_7. Various studies have indicated an increase in the number of spikes and number of grains per spike in wheat crops with the application of nitrogen (Galindo *et al.*, 2022; Ibarra-Villarreal *et al.*, 2023). Insufficient nitrogen levels can lead to shorter spikes, while optimal nitrogen levels can contribute to longer spikes (Bader *et al.*, 2021). Additionally, Díaz-Zorita *et al.* (2009) have reported positive effects of *Azospirillum* on the number of spikes.

Straw and grain yield

The observation of the byproduct of wheat after harvesting showed that, the maximum yield of the straw was reported in T_4 (60.7 q/ha) and the minimum was in T_9 (45.6 q/ha) as shown in Fig. 8(a). Straw yield for T_1 was found to be significantly different ($p < 0.05$) from T_2, T_3 and T_4. The usages of biofertilizers, organic manure and vermicompost enhance the vegetative growth of the wheat plant (Galindo *et al.*, 2022; Ibarra-Villarreal *et al.*, 2023).

The number of grains per spike is a crucial factor that directly influences the overall grain yield of the wheat crop (Bader *et al.*, 2021; Darjee *et al.*, 2023). A higher number of grains per spike generally had greater productivity. In the present study, T_4 had the highest number of grains per spike (28.6), while T_9 had the lowest (23.6) grains per spike, which significantly affects the grain yield as recorded the highest grain yield was in T_4 (45.01 q/ha) and, the lowest was in T_7 (30.2 q/ha) as shown in Fig. 8(b).

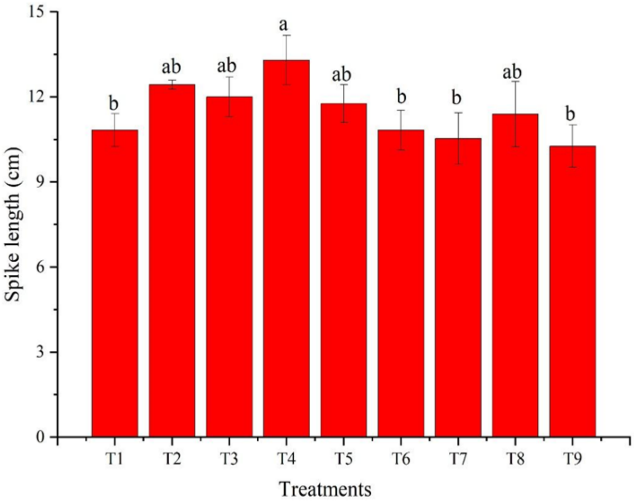

Fig. 5. *Spike length (cm) of wheat with different INM treatments where lowercase letters represent the significance difference as evaluated by Tukey's post hoc test ($p < 0.05$)*

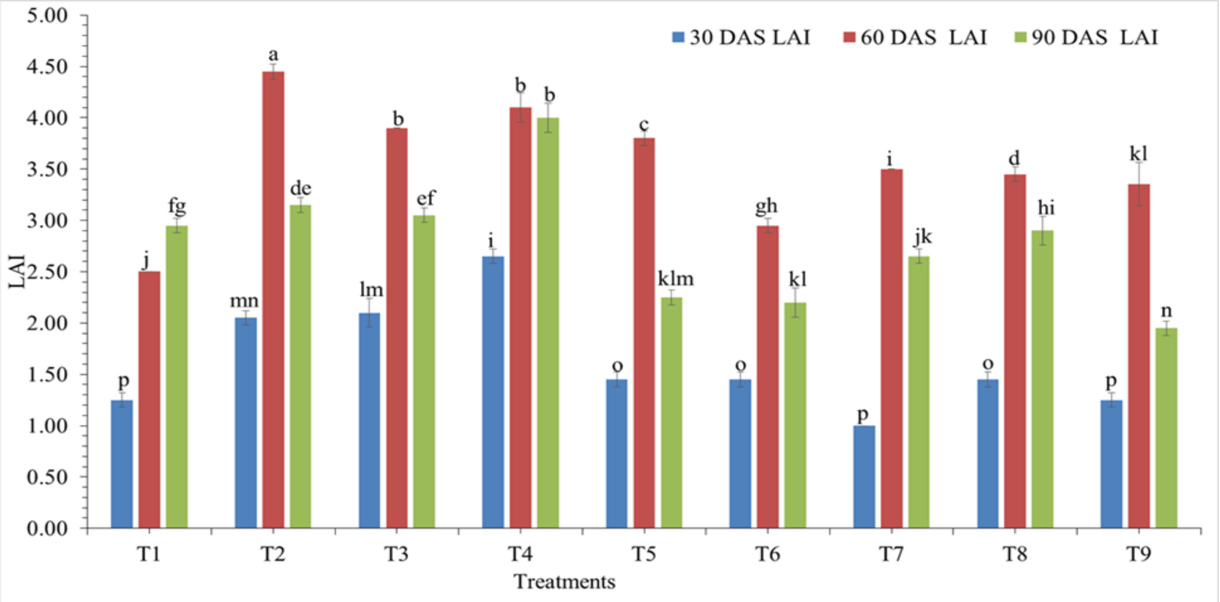

Fig. 6. *Leaf Area Index of wheat with different INM treatments where lowercase letters represent the significance difference as evaluated by Tukey's post hoc test (p < 0.05)*

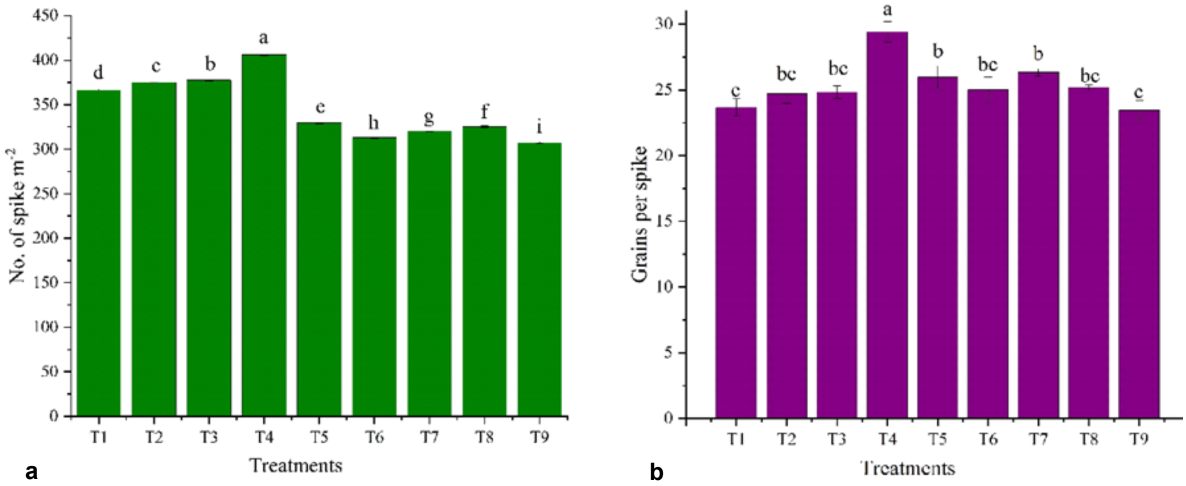

Fig. 7. *(a) Number of spike m^{-2} and (b) Number of grains per spikes, where lowercase letters represent the significant dif-*

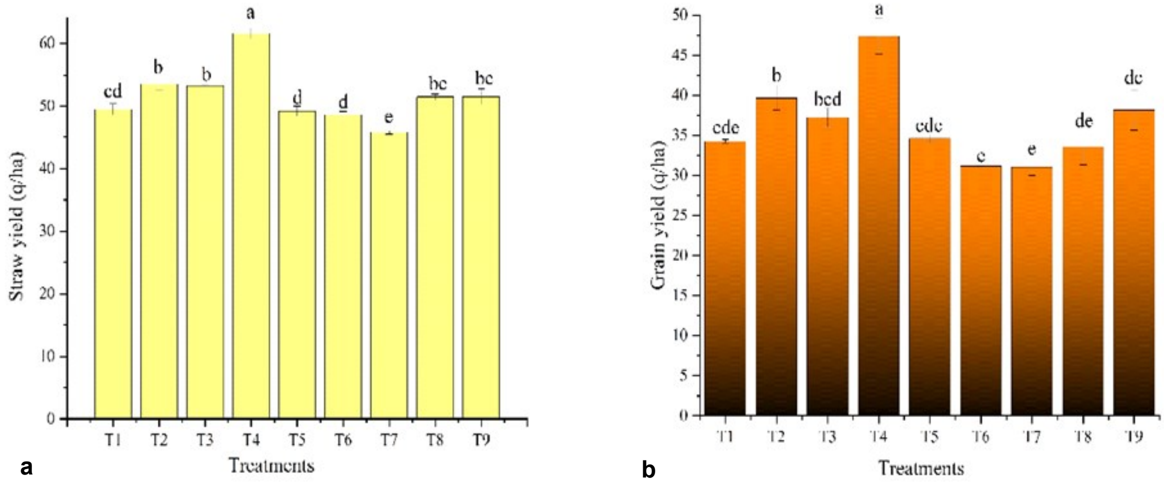

Fig. 8. *(a) Straw yield (q/ha) (b) Grain yield of wheat, where lowercase letters represent the significance difference as evaluated by Tukey's post hoc test (p < 0.05)*

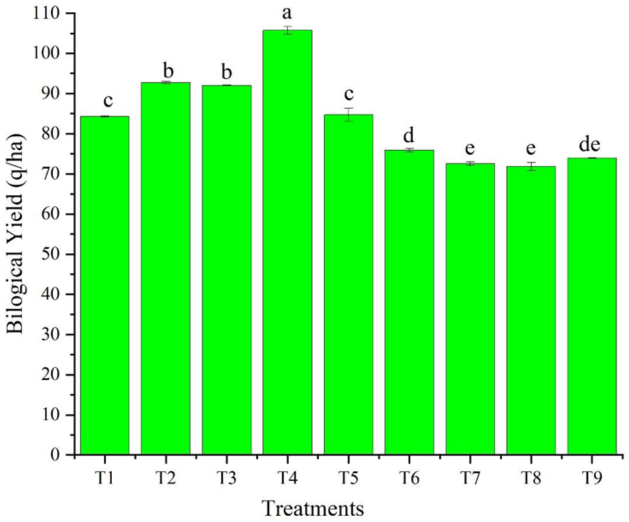

Fig. 9. *Impact of different INM treatments on the biological yield, where lowercase letters represent the significance difference as evaluated by Tukey's post hoc test ($p < 0.05$)*

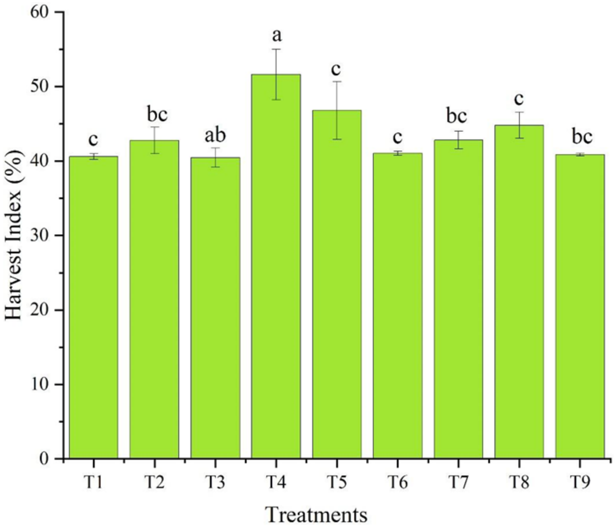

Fig. 10. *Impact of different INM treatments on the Harvest Index, where lowercase letters represent the significance difference as evaluated by Tukey's post hoc test ($p < 0.05$)*

Biological yield

The findings of this study underscore the significance of biological yield characteristics in determining productivity. The highest biological yield was recorded in the T_4 (104.8 q/ha) and the lowest in T_7 (72.5 q/ha), as shown in Fig. 9. Biological yield of T_1 was found to be significantly different ($p < 0.05$) from all treatments except T_5. This observed variance in biological yield highlights the diverse genetic influences on yield potential among the tested varieties. Such insights shed light on the complex interplay between genetic factors and agronomic traits, crucial for optimizing biological yield in crop cultivation. Biological yield is a crucial factor that directly influences the overall grain yield of the wheat crop (Bader *et al.*, 2021; Darjee *et al.*, 2023).

Harvest Index

Harvest Index (HI) denotes the ratio of the grain yield of a crop, to the total biomass (Biological yield) of the plant at harvest (Ruiz *et al.*, 2023). It serves as a metric to assess a crop's efficiency in converting its overall biomass into edible or economically valuable produce (Campoy *et al.*, 2020). Integrated fertilization, a strategy that amalgamates various nutrient management approaches, is crucial in optimizing resource allocation within the wheat plant. By offering a balanced and comprehensive method for nutrient supplementation, integrated fertilization ensures that the crop receives the essential elements for robust growth and grain development (Campoy *et al.*, 2020).

The maximum HI (55.01%) was reported in T_4, and it was significantly (34%) higher than the RDF, which was followed by T_5 (50.7%), as shown in Fig. 10. Conversely, the minimum HI was recorded in T_1 (40.97%), significantly lower than T_4. This indicates that optimum grain yield cannot be achieved by using conventional chemical fertilizers without incorporating biofertilizers and organic amendments. Similarly, Bhardwaj *et al.* (2021) reported higher HI for wheat. In another study, Bastakoti *et al.* (2017) also reported the synergistic effects of *Azospirillum,* PSB, and organic inputs on enhancing biological and grain yield.

Conclusion

The results of the present study revealed significant insights into the effects of different INM treatments on the growth and development of wheat genotype PBW 590, along with improvement in soil quality. The plant height exhibited variations due to diverse treatment doses, with the most pronounced impact observed from 60 DAS onward. The treatment T_4, which included a combination of 70% RDF + 2.5% *Azospirillum* + 2.5% PSB + 20% FYM + 5% Vermicompost, displayed the highest plant height, surpassing the RDF by 6.17%.

The INM treatments positively influenced the LAI. This suggests that the INM approach, particularly T_4, significantly enhances the leaf area and overall canopy development, potentially leading to improved photosynthetic efficiency and higher grain yields. HI showed notable improvements in treatments incorporating biofertilizers and vermicompost, with T_4 exhibiting the highest HI, indicating better resource allocation towards edible yield. However, a decrease in HI was attributed to foliar fungal infections, highlighting the impact of biotic stresses on harvest efficiency. Nutrient (N, P and K) availability was also significantly influenced by different doses of fertilizers under INM treatments. The study indicated the integration of various components, such as biofertilizers and vermicompost, in enhancing plant height, leaf area, harvest index, organic carbon content, and nutrient availability. This contributes to understanding sustainable agriculture, particularly in the context of changing agricultural practices and environmental concerns.

Conflict of interest

The authors declare that they have no conflict of interest.

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