



RESEARCH ARTICLE

# Effect of establishment methods and nutrient management on soil microbial population, enzyme activity and yield of basmati rice (*Oryza sativa* L.)

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## Abstract

A field experiment was conducted at the Agricultural College and Research Institute, Madurai, Tamil Nadu during *rabi* 2023 and *kharif* 2024 to study the effect of establishment methods and nutrient management on soil microbial population, enzyme activity and yield of basmati rice (*Oryza sativa* L.). The experiment was laid out in a split-plot design with three establishment methods in the main plot: mechanical transplanting (M<sub>1</sub>), transplanting under saturated soil conditions (M<sub>2</sub>) and conventional transplanting (M<sub>3</sub>) and seven nutrient management practices in the subplot: ICAR blanket recommendation for basmati (S<sub>1</sub>), Soil Test Crop Response (STCR) recommendation (S<sub>2</sub>), 75 % inorganic + 25 % organic N equivalent (S<sub>3</sub>), 50 % inorganic + 50 % organic N equivalent (S<sub>4</sub>), 25 % inorganic + 75 % organic N equivalent (S<sub>5</sub>), 100 % organic N equivalent (S<sub>6</sub>) and absolute control (S<sub>7</sub>). Results revealed that M<sub>1</sub>S<sub>6</sub> (mechanical transplanting with 100 % organic as N equivalent) recorded the higher microbial count and enzyme activity. In terms of yield, mechanical transplanting with STCR based nutrient management (M<sub>1</sub>S<sub>2</sub>) produced the highest yield, followed closely by M<sub>1</sub>S<sub>3</sub> (mechanical transplanting with application of 75 % inorganic + 25 % organic as N equivalent), which was statistically on par with M<sub>1</sub>S<sub>2</sub>. In conclusion, although M<sub>1</sub>S<sub>2</sub> achieved the highest yield, M<sub>1</sub>S<sub>6</sub> emerged as the most effective for enhancing microbial population and enzyme activity, thereby promoting soil health. M<sub>1</sub>S<sub>3</sub> offered a balanced trade-off by achieving high yield while integrating organic nutrients, emphasizing environmental sustainability and soil health. Hence, M<sub>1</sub>S<sub>3</sub> is recommended as a practical and eco-friendly option for sustainable basmati rice cultivation, providing harmonious balance between productivity and ecological wellbeing.

**Keywords:** dehydrogenase; mechanical transplanting; organics; phosphatase; urease

## Introduction

The slogan "RICE IS LIFE" underscores the significance of rice, particularly in India, where it is a cornerstone of national food security and a livelihood source for millions of rural households (1). Basmati rice stands out for its exceptional quality traits, including its aromatic fragrance, long grains and superior cooking properties, which make it highly valued both domestically and internationally (2). Its unique flavour, low glycemic index and rich nutrient content, including fibre, vitamins and minerals, also contribute to its growing popularity among health-conscious consumers (3).

India is the world's leading producer and exporter of basmati rice, contributing to nearly 70 % of global production and more than 20 % of the country's total agricultural export value. In the fiscal year 2023-24, India exported approximately

4.45 million tonnes of basmati rice, generating substantial revenue (4). Basmati cultivation is primarily concentrated in the Himalayan foothills of states such as Punjab, Haryana and Uttar Pradesh, where the agro-climatic conditions are ideal for its growth (5). However, Tamil Nadu's contribution to basmati rice cultivation is relatively limited due to unfavourable agro-climatic conditions and challenges in adopting optimal agronomic practices. This is primarily due to consistently high temperatures that affect aroma development, unpredictable rainfall patterns during critical stages and less suitable soils with poor water retention capacity.

Rice cultivation in India predominately follows the transplanting method, where seedlings are raised in nurseries and then transplanted into flooded or puddled fields (6). However, emerging practices, such as transplanting under saturated soil conditions and mechanical transplanting, have

shown promise in enhancing productivity and sustainability (7). Among these, mechanical transplanting has demonstrated the potential to reduce labour costs and increase profitability (8). Additionally, effective nutrient management through Integrated Nutrient Management (INM) practices is essential to improve soil fertility and achieve higher yields (9). The success of rice cultivation, particularly basmati, depends not only on the right establishment methods and nutrient management but also on maintaining a healthy soil ecosystem (10). This involves fostering a robust microbial population and promoting enzyme activity, both of which play key roles in nutrient cycling and soil health (11). Microbial populations in the soil, including bacteria, fungi and actinomycetes, facilitate breaking down organic matter, facilitating nutrient availability and improving soil structure (12). The composition and abundance of these microbial communities can significantly impact crop growth and productivity (13).

Enzyme activity in the soil is another critical factor, as enzymes catalyse essential biochemical processes that affect nutrient mineralization, organic matter decomposition and soil nutrient availability (14). Key enzymes involved in nutrient cycling, such as urease, dehydrogenase and phosphatase, play significant roles in nitrogen, carbon and phosphorus availability, all of which are crucial for plant growth (15). A healthy microbial population and efficient enzyme activity enhance nutrient cycling, contributing to improved soil fertility, plant health and ultimately, higher rice yields (16). There is a direct relationship between microbial population, enzyme activity and rice yield. A high microbial population often correlates with better soil fertility and enhanced nutrient cycling, leading to improved crop growth and higher yields (17). Likewise, robust enzyme activity ensures the efficient breakdown of organic materials, releasing nutrients like nitrogen and phosphorus that are critical for rice development. These processes not only support plant health but also contribute to the overall yield and quality of the crop (18). In the context of basmati rice,

optimizing microbial population and enzyme activity can significantly enhance the yield and quality of the crop. For instance, mechanical transplanting with 100 % organic nutrient management ( $M_1S_6$ ) has been shown to improve microbial counts and enzyme activity, thus promoting better soil health. Similarly, practices like mechanical transplanting combined with STCR based nutrient management ( $M_1S_2$ ) have been associated with higher yields, demonstrating the positive impact of targeted nutrient management on crop productivity (19). These practices not only boost immediate yield but also contribute to long term soil fertility, making them essential for sustainable basmati rice cultivation (20).

Given these considerations, the present study was designed to evaluate the effect of establishment methods and nutrient management practices on microbial population, enzyme activity and yield of basmati rice (*Oryza sativa* L.) under Tamil Nadu's agro-climatic conditions. By examining the interplay between establishment techniques and nutrient management, this research aims to understand their combined impact on soil health, microbial dynamics, enzyme activity and overall crop productivity, ultimately guiding sustainable agricultural practices for improving basmati rice cultivation in the region.

## Materials and Methods

### Study location and meteorological parameters

Field experiments were conducted at the Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai (9°54' N and 78°54' E with an altitude of 147 m above mean sea level), Tamil Nadu during the *rabi* 2023 and *kharif* 2024 seasons. During the *rabi* 2023 cropping season, total rainfall was 30 mm over 7 rainy days, with average maximum and minimum temperature of 33.5 °C and 19.2 °C, respectively (Fig. 1). In contrast, during *kharif* 2024, total rainfall was 202.06 mm across 16 rainy days, with maximum and minimum temperature of 34.1 °C and 28.8 °C, respectively (Fig. 2).

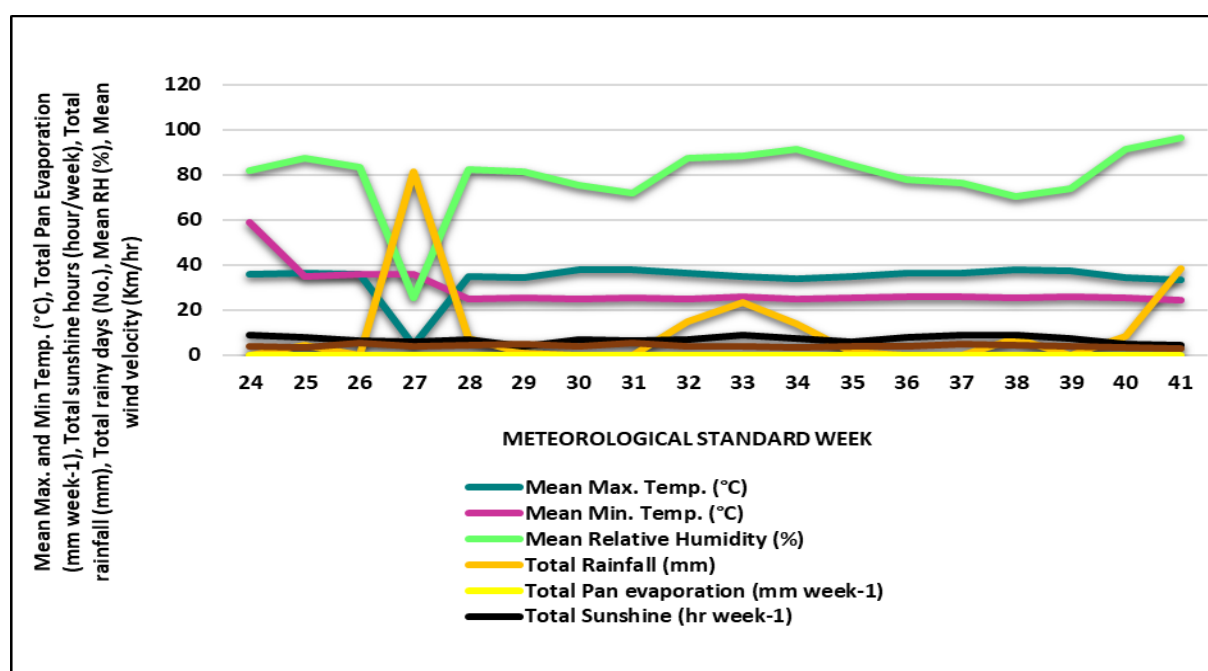


Fig. 1. Weekly weather data during the cropping period of *rabi* 2023

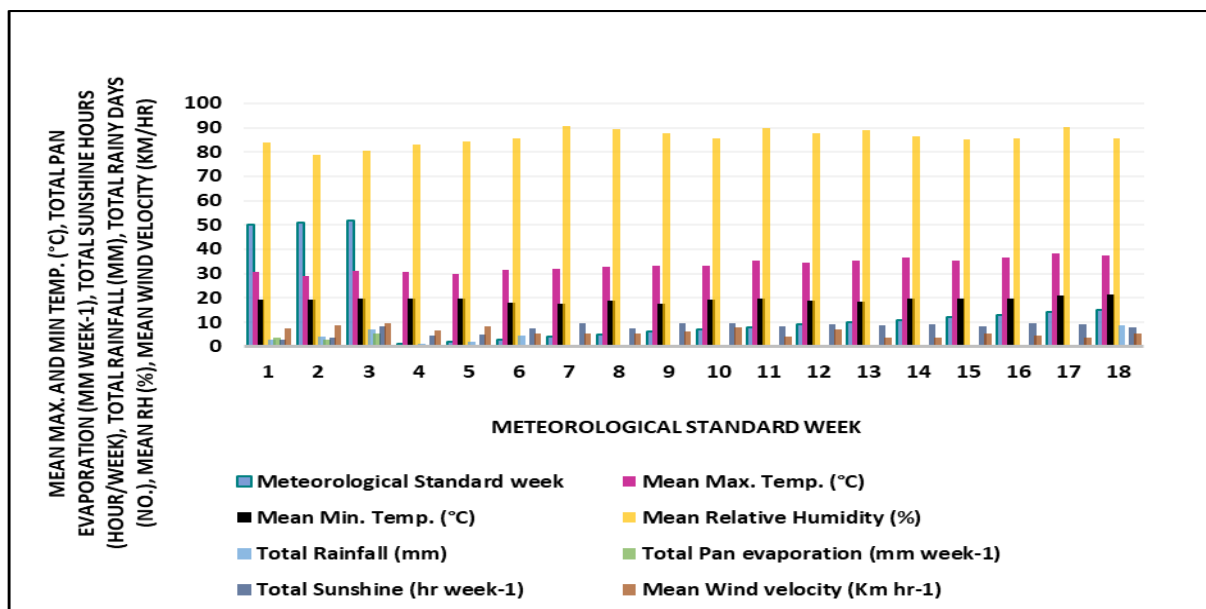


Fig. 2. Weekly weather data during the cropping period of Kharif 2024.

### Preliminary soil analysis

The experimental field soil was classified as sandy clay loam using the textural triangle method and was medium in available nitrogen (221.0 and 203.2 kg ha<sup>-1</sup>), low in available phosphorus (19.5 and 18.9 kg ha<sup>-1</sup>) and medium in available potassium (284.0 and 272.0 kg ha<sup>-1</sup>) in both seasons.

### Experimental design and treatment details

Field experiments were laid out in split plot design with three replications. Main plot contained three establishment methods, viz. mechanical transplanting (M<sub>1</sub>), transplanting under saturated soil conditions (M<sub>2</sub>) and conventional transplanting (M<sub>3</sub>). Whereas, subplots contains seven nutrient management practices, viz. blanket recommendation given by ICAR for basmati 90:30:30 kg of NPK ha<sup>-1</sup> (S<sub>1</sub>), STCR recommendation (S<sub>2</sub>), 75 % inorganic + 25 % organic as N equivalent (S<sub>3</sub>), 50 % inorganic + 50 % organic as N equivalent (S<sub>4</sub>), 25 % inorganic + 75 % organic as N equivalent (S<sub>5</sub>), 100 % organic as N equivalent (S<sub>6</sub>) and absolute control (S<sub>7</sub>). Each plot had dimensions of 4 m × 4.5 m and was separated by 1 m wide irrigation and buffer channels. The net plot size was 3.8 m × 4 m.

### Crop and variety

Pusa Basmati 1847, released by IARI in 2021, is an improved version of Pusa Basmati 1509 developed for commercial cultivation. It is a semi dwarf variety (120 cm plant height) with a duration of 120 days, resistant to bacterial blight and blast diseases and has an average yield potential of 5770 kg ha<sup>-1</sup>.

### Microbial analysis

#### Enumeration of total bacteria, fungi and actinomycetes

The soil samples were collected post-harvest, serially diluted to count the total bacteria, fungi and actinomycetes and the population of each group was calculated and expressed as colony-forming units (cfu) per gram of dry soil.

#### Serial dilution and plating technique

1 g of dry soil was transferred to a 100 mL water blank and shaken for 15 min to obtain a 10<sup>-2</sup> dilution. Serial dilutions

were prepared up to 10<sup>-8</sup>. 1 mL aliquots of appropriate dilutions were plated in triplicate on selective media. After solidification, the petri plates were incubated in an inverted position, either at room temperature or in an incubator, for 2-7 days. Colonies were counted after 2 days (bacteria), 3-4 days (fungi) and 7 days (actinomycetes).

(Note: Typically, a 10<sup>-8</sup> dilution is used for bacteria, 10<sup>-5</sup> dilution for actinomycetes and 10<sup>-4</sup> dilution for fungi when soil samples are used for enumeration). The population of each group of organisms was calculated using the following formula:

No. of Colony Forming Units (CFUs) per gram of sample =

$$\frac{\text{Total number of CFUs} \times \text{Dilution factor}}{\text{Quantity of soil sample taken on dry weight basis}}$$

(Eqn. 1)

### Soil enzyme analysis

#### Urease

The urease activity in soil was estimated from post-harvest soil samples using the method suggested elsewhere (21). To measure urease activity, 1 g of soil sample was taken and treated with 10 mL of 0.05 mol urea solution, after which the mixture was incubated for 2 hrs at 37 °C. Following incubation, the reaction was stopped by adding 25 mL of 0.5 mol sodium hydroxide (NaOH). The released ammonia (NH<sub>3</sub>) was then determined through distillation using a micro-Kjeldahl apparatus and the collected NH<sub>3</sub> was measured by titration with standard 0.1 N hydrochloric acid (HCl). Finally, urease activity was calculated using a standard curve and expressed as µg of NH<sub>3</sub> released g<sup>-1</sup> soil day<sup>-1</sup>.

#### Phosphatase

Phosphatase activity in the soil was measured using the method described previously (22). For this, 1 g of soil sample was mixed with 3 mL of p-nitrophenol phosphate and 3.5 mL of 0.1 mol Modified Universal Buffer (MUB) and the mixture was incubated for 4 hrs. After incubation, 1 mL of 0.5 mol calcium chloride and 4 mL of 0.5 mol sodium hydroxide were

added. The mixture was then filtered and the intensity of the developed colour was measured at 420 nm using a spectrophotometer (Model: UV-1800, Shimadzu, Japan). Finally, phosphatase activity was calculated using a standard graph and expressed as  $\mu\text{g}$  of PNP released per gram of soil per day ( $\mu\text{g}$  PNP  $\text{g}^{-1}$  soil  $\text{day}^{-1}$ ).

#### Dehydrogenase

Dehydrogenase activity in the soil was measured using the method described earlier (23). For this, 1 g of soil sample was treated with 10 mL of phosphate buffer containing 1 % 2,3,5-triphenyl tetrazolium chloride and incubated at room temperature for 15 hrs. After incubation, 40 mL of 90 % carbon tetrachloride was added and mixed thoroughly. The concentration of triphenyl formazan (TPF) was then measured at 530 nm using a spectrophotometer. At last, dehydrogenase activity was calculated from a standard graph and expressed as  $\mu\text{g}$  of TPF released per gram of soil per day ( $\mu\text{g}$  TPF  $\text{g}^{-1}$  soil  $\text{day}^{-1}$ ).

#### Yield

Grain yield and straw yield were computed from each net plot after harvesting, threshing, winnowing and cleaning. Grain yield was adjusted to 14 % moisture content and expressed in  $\text{kg ha}^{-1}$ . Similarly, the straw yield was determined by sun drying the biomass for three consecutive days, after which the final weight was measured and expressed in  $\text{kg ha}^{-1}$ .

#### Statistical analysis

All evaluated traits were analysed using analysis of variance (ANOVA) in R Studio (version 4.2.1) on a Windows platform. Significant differences between treatment means were determined using Fisher's Least Significant Difference (LSD) test at a 5 % significance level, with non-significant results denoted as 'NS'. The effect of various nutrient management strategies on yield was illustrated using boxplots, while relationships among traits were analysed through Pearson correlation coefficients. The boxplots were generated using KAU GRAPES (version 1.1.0), a General R-based Analysis Platform Empowered by Statistics.

## Results

#### Yield

Yield represents the ultimate performance of crops, as it is shaped by various management practices and influenced by environmental conditions. Timely and efficient input use within a given environment ensures optimal resource use and maximizes economic returns. Moreover, both grain and straw yield varied significantly depending on the methods of establishment and the implementation of INM strategies.

The effects of establishment methods and nutrient management practices on both grain and straw yield exhibited similar trends. Among the establishment methods, mechanical transplanting ( $M_1$ ) consistently recorded the highest grain and straw yields during both the seasons which achieved the grain and straw yield of 4476.9 and 7023.3  $\text{kg ha}^{-1}$  during *rabi* 4801.6 and 7204  $\text{kg ha}^{-1}$  during *kharif* seasons, respectively (Table 1). This was followed by conventional transplanting ( $M_3$ ), which registered grain yields of 4313.5 and 4647.6  $\text{kg ha}^{-1}$  and straw yields of 6774.3 and 6973  $\text{kg ha}^{-1}$

during *rabi* and *kharif* seasons individually. In contrast, the lowest yields were observed under transplanting under saturated soil conditions ( $M_2$ ), with grain yields of 4196.8 and 4500  $\text{kg ha}^{-1}$  and straw yields of 6564.3 and 6751.6  $\text{kg ha}^{-1}$  over the two seasons. Regarding nutrient management practices, fertilizer application based on STCR recommendation ( $S_2$ ) produced significantly higher grain and straw yields compared to other nutrient management practices, which registered the grain yield of (5120.4 and 5427.8  $\text{kg ha}^{-1}$ ) and straw yield of (7806.2 and 8142.6  $\text{kg ha}^{-1}$ ) during *rabi* and *kharif* seasons, respectively. In contrast, lowest yield was observed under absolute control ( $S_7$ ) with grain yield of (3396.3 and 3729.6  $\text{kg ha}^{-1}$ ) and straw yields of (5004.9 and 5596.3  $\text{kg ha}^{-1}$ ) over the two seasons. Regarding interaction, combination of mechanical transplanting with STCR based nutrient management ( $M_1S_2$ ) recorded the highest grain yield of (5272.2 and 5527.8  $\text{kg ha}^{-1}$ ) and straw yield of (8018.5 and 8294.4  $\text{kg ha}^{-1}$ ) during *rabi* and *kharif* seasons, respectively. However, it was statistically on par with mechanical transplanting combined with 75 % inorganic + 25 % organic nitrogen as N equivalent ( $S_3$ ), which achieved the grain yield of (5127 and 5461.1  $\text{kg ha}^{-1}$ ) and straw yield of (7744.4 and 8194.4  $\text{kg ha}^{-1}$ ) during the respective seasons. In contrast, the lowest yield was recorded under transplanting under saturated soil condition with absolute control ( $M_2S_7$ ) which logged the grain yield of (3283.3 and 3616.7  $\text{kg ha}^{-1}$ ) and straw yield of (4881.5 and 5427.8  $\text{kg ha}^{-1}$ ) during *rabi* and *kharif* seasons respectively.

#### Microbial population

Microbial populations (fungi, bacteria and actinomycetes) play a pivotal role in soil health and crop productivity, serving as an indicator of biological activity and nutrient cycling in the soil. These microorganisms are influenced by diverse management practices, including various nutrient management practices and crop establishment methods. Proper integration of nutrient management strategies fosters microbial proliferation, which in turn, enhances soil enzymatic activity and nutrient availability.

#### Bacterial population

Soil bacterial population was significantly influenced by both diverse establishment methods and nutrient management practices during both the seasons. Mechanical transplanting ( $M_1$ ) had the highest bacterial populations ( $68.2 \times 10^7$  cfu  $\text{g}^{-1}$  in *rabi*;  $71.8 \times 10^7$  cfu  $\text{g}^{-1}$  in *kharif*) (Table 2). This was closely followed by transplanting under saturated soil conditions ( $M_2$ ), which registered the values of ( $67.1 \times 10^7$  cfu  $\text{g}^{-1}$  and  $70.8 \times 10^7$  cfu  $\text{g}^{-1}$ ) during both the seasons. In contrast, the minimum bacterial population was observed under conventional transplanting ( $M_3$ ), accounting ( $66.1 \times 10^7$  and  $69.9 \times 10^7$  cfu  $\text{g}^{-1}$ ) over the two seasons. Regarding nutrient management practices, application of 100 % organic as N equivalent ( $S_6$ ) resulted highest bacterial population of ( $75.2 \times 10^7$  and  $79.9 \times 10^7$  cfu  $\text{g}^{-1}$ ) during *rabi* and *kharif* seasons, correspondingly. Conversely, absolute control ( $S_7$ ) recorded the minimum bacterial population ( $54.7 \times 10^7$  and  $59.4 \times 10^7$  cfu  $\text{g}^{-1}$ ). On interaction, the combination of mechanical transplanting with 100 % organic as N equivalent ( $M_1S_6$ ) achieved the highest bacterial population of ( $76.0 \times 10^7$  and  $80.7 \times 10^7$  cfu  $\text{g}^{-1}$ ) during *rabi* and *kharif* seasons, separately.



**Table 1.** Effect of establishment methods and nutrient management practices on grain yield (kg ha<sup>-1</sup>) and straw yield (kg ha<sup>-1</sup>) of basmati rice during *rabi* 2023 and *kharif* 2024

Treatment	Grain yield (kg ha <sup>-1</sup> )		Straw yield (kg ha <sup>-1</sup> )	
	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>
<b>M- Establishment methods</b>				
<b>M<sub>1</sub></b>	4476.9 <sup>a</sup>	4801.6 <sup>a</sup>	7023.3 <sup>a</sup>	7204.0 <sup>a</sup>
<b>M<sub>2</sub></b>	4196.8 <sup>b</sup>	4500.0 <sup>b</sup>	6564.3 <sup>b</sup>	6751.6 <sup>b</sup>
<b>M<sub>3</sub></b>	4313.5 <sup>b</sup>	4647.6 <sup>b</sup>	6774.3 <sup>b</sup>	6973.0 <sup>b</sup>
<b>SEd</b>	120.47	127.42	192.18	198.42
<b>CD(P=0.05)</b>	260.21	279.05	407.63	418.67
<b>S- Nutrient management practices</b>				
<b>S<sub>1</sub></b>	4574.1 <sup>c</sup>	4796.3 <sup>c</sup>	7331.5 <sup>c</sup>	7196.3 <sup>c</sup>
<b>S<sub>2</sub></b>	5120.4 <sup>a</sup>	5427.8 <sup>a</sup>	7806.2 <sup>a</sup>	8142.6 <sup>a</sup>
<b>S<sub>3</sub></b>	4944.2 <sup>b</sup>	5277.8 <sup>b</sup>	7671.6 <sup>b</sup>	7918.5 <sup>b</sup>
<b>S<sub>4</sub></b>	4418.5 <sup>c</sup>	4825.9 <sup>c</sup>	6996.3 <sup>c</sup>	7240.7 <sup>c</sup>
<b>S<sub>5</sub></b>	4088.5 <sup>d</sup>	4396.3 <sup>d</sup>	6617.9 <sup>d</sup>	6596.3 <sup>d</sup>
<b>S<sub>6</sub></b>	3761.1 <sup>e</sup>	4094.4 <sup>e</sup>	6082.7 <sup>e</sup>	6142.6 <sup>e</sup>
<b>S<sub>7</sub></b>	3396.3 <sup>f</sup>	3729.6 <sup>f</sup>	5004.9 <sup>f</sup>	5596.3 <sup>f</sup>
<b>SEd</b>	120.52	127.78	177.11	189.07
<b>CD(P=0.05)</b>	255.50	274.78	384.33	412.17
<b>M x S (Interaction effect)</b>				
<b>M<sub>1</sub>S<sub>1</sub></b>	4711.1 <sup>c</sup>	4905.6 <sup>c</sup>	7496.3 <sup>c</sup>	7361.1 <sup>c</sup>
<b>M<sub>1</sub>S<sub>2</sub></b>	5272.2 <sup>a</sup>	5527.8 <sup>a</sup>	8018.5 <sup>a</sup>	8294.4 <sup>a</sup>
<b>M<sub>1</sub>S<sub>3</sub></b>	5127.0 <sup>b</sup>	5461.1 <sup>b</sup>	7744.4 <sup>b</sup>	8194.4 <sup>b</sup>
<b>M<sub>1</sub>S<sub>4</sub></b>	4477.8 <sup>c</sup>	5044.4 <sup>c</sup>	7200.0 <sup>c</sup>	7566.7 <sup>c</sup>
<b>M<sub>1</sub>S<sub>5</sub></b>	4327.8 <sup>d</sup>	4583.3 <sup>d</sup>	7131.5 <sup>d</sup>	6877.8 <sup>d</sup>
<b>M<sub>1</sub>S<sub>6</sub></b>	3955.6 <sup>e</sup>	4288.9 <sup>e</sup>	6377.8 <sup>e</sup>	6433.3 <sup>e</sup>
<b>M<sub>1</sub>S<sub>7</sub></b>	3466.7 <sup>f</sup>	3800.0 <sup>f</sup>	5194.4 <sup>f</sup>	5700.0 <sup>f</sup>
<b>M<sub>2</sub>S<sub>1</sub></b>	4438.9 <sup>d</sup>	4672.2 <sup>d</sup>	7142.6 <sup>d</sup>	7011.1 <sup>d</sup>
<b>M<sub>2</sub>S<sub>2</sub></b>	4988.9 <sup>a</sup>	5322.2 <sup>a</sup>	7655.6 <sup>a</sup>	7983.3 <sup>a</sup>
<b>M<sub>2</sub>S<sub>3</sub></b>	4800.0 <sup>b</sup>	5133.3 <sup>b</sup>	7622.2 <sup>b</sup>	7700.0 <sup>b</sup>
<b>M<sub>2</sub>S<sub>4</sub></b>	4438.9 <sup>c</sup>	4661.1 <sup>c</sup>	6657.4 <sup>c</sup>	6994.4 <sup>c</sup>
<b>M<sub>2</sub>S<sub>5</sub></b>	3855.6 <sup>d</sup>	4188.9 <sup>d</sup>	6124.1 <sup>d</sup>	6283.3 <sup>d</sup>
<b>M<sub>2</sub>S<sub>6</sub></b>	3572.2 <sup>e</sup>	3905.6 <sup>e</sup>	5866.7 <sup>e</sup>	5861.1 <sup>e</sup>
<b>M<sub>2</sub>S<sub>7</sub></b>	3283.3 <sup>f</sup>	3616.7 <sup>f</sup>	4881.5 <sup>f</sup>	5427.8 <sup>f</sup>
<b>M<sub>3</sub>S<sub>1</sub></b>	4572.2 <sup>c</sup>	4811.1 <sup>c</sup>	7355.6 <sup>c</sup>	7216.7 <sup>c</sup>
<b>M<sub>3</sub>S<sub>2</sub></b>	5100.0 <sup>a</sup>	5433.3 <sup>a</sup>	7744.4 <sup>a</sup>	8150.0 <sup>a</sup>
<b>M<sub>3</sub>S<sub>3</sub></b>	4905.6 <sup>b</sup>	5238.9 <sup>b</sup>	7648.1 <sup>b</sup>	7861.1 <sup>b</sup>
<b>M<sub>3</sub>S<sub>4</sub></b>	4338.9 <sup>c</sup>	4772.2 <sup>c</sup>	7131.5 <sup>c</sup>	7161.1 <sup>c</sup>
<b>M<sub>3</sub>S<sub>5</sub></b>	4083.3 <sup>d</sup>	4416.7 <sup>d</sup>	6598.1 <sup>d</sup>	6627.8 <sup>d</sup>
<b>M<sub>3</sub>S<sub>6</sub></b>	3755.6 <sup>e</sup>	4088.9 <sup>e</sup>	6003.7 <sup>e</sup>	6133.3 <sup>e</sup>
<b>M<sub>3</sub>S<sub>7</sub></b>	3438.9 <sup>f</sup>	3772.2 <sup>f</sup>	4938.9 <sup>f</sup>	5661.1 <sup>f</sup>
<b>SEd</b>	119.94	128.19	183.41	191.47
<b>CD(P=0.05)</b>	256.67	274.34	387.00	411.67

Means followed by the same letter do not differ statistically among themselves by Duncan's multiple range test, ( $p \leq 0.05$ ).

SEd: Standard Error of Difference between means. CD: Critical Difference at a 5 % significance level

M1-Mechanical Transplanting, M2-Transplanting under saturated soil condition, M3-Conventional Transplanting. S1 -Blanket recommendation given by ICAR for basmati, S2- STCR recommendation, S3 -75 % Inorganic + 25 % Organic as N equivalent, S4 -50 % Inorganic + 50 % Organic as N equivalent, S5 -25 % Inorganic + 75 % Organic as N equivalent, S6 -100 % Organic as N equivalent, S7 -Absolute control.

Whereas, lowest bacterial population was observed under conventional transplanting and absolute control (M<sub>3</sub>S<sub>7</sub>), which enumerated the values of ( $52.8 \times 10^7$  and  $57.5 \times 10^7$  cfu g<sup>-1</sup>) across the two seasons.

### Fungal population

Soil fungal population was markedly influenced by the establishment methods and nutrient management practices during *rabi* and *kharif* seasons of this study. Amid the diverse establishment methods, mechanical transplanting (M<sub>1</sub>) showed the highest fungal populations ( $33.9 \times 10^4$  cfu g<sup>-1</sup> in *rabi*;  $37.1 \times 10^4$  cfu g<sup>-1</sup> in *kharif*) (Table 2). However, it was on par with transplanting under saturated soil condition (M<sub>2</sub>) which logged the values of ( $32.9 \times 10^4$  cfu g<sup>-1</sup> and  $36.1 \times 10^4$  cfu g<sup>-1</sup>) over the two seasons. However, the minimum fungal population was noticed under conventional transplanting (M<sub>3</sub>) which recorded the values of ( $32.1 \times 10^4$  cfu g<sup>-1</sup> and  $35.2 \times 10^4$  cfu g<sup>-1</sup>) during both the seasons. In terms of nutrient management strategies, 100 % organic as N equivalent (S<sub>6</sub>) resulted the highest fungal population ( $41.2 \times 10^4$  cfu g<sup>-1</sup> and

$44.6 \times 10^4$  cfu g<sup>-1</sup>) over the two seasons. Conversely, absolute control (S<sub>7</sub>) registered the lowest fungal population. The interaction effect revealed that mechanical transplanting with 100 % organic as N equivalent (M<sub>1</sub>S<sub>6</sub>) ( $10^4$  cfu g<sup>-1</sup>) enumerated the maximum fungal population ( $41.9 \times 10^4$  cfu g<sup>-1</sup> and  $45.1 \times 10^4$  cfu g<sup>-1</sup>) during both the seasons. Whereas, population was observed minimum under conventional transplanting with absolute control (M<sub>3</sub>S<sub>7</sub>), recorded ( $23.7 \times 10^4$  cfu g<sup>-1</sup> and  $26.4 \times 10^4$  cfu g<sup>-1</sup>) during both the seasons.

### Actinomycetes population

Actinomycetes populations were greatly influenced by both establishment methods and nutrient management practices over the two seasons. Regarding establishment methods, mechanical transplanting (M<sub>1</sub>) recorded the highest actinomycetes population of ( $20.0 \times 10^5$  cfu g<sup>-1</sup> and  $21.4 \times 10^5$  cfu g<sup>-1</sup>) during both the seasons (Table 2). In contrast, the lowest population was observed under conventional transplanting (M<sub>3</sub>), which accounted the values of ( $19.0 \times 10^5$  cfu g<sup>-1</sup> and  $20.4 \times 10^5$  cfu g<sup>-1</sup>) over the two seasons. Regarding

**Table 2.** Effect of establishment methods and nutrient management practices on microbial populations of basmati rice during *rabi* 2023 and *kharif* 2024

Treatment	Bacteria ( $10^7$ cfu g <sup>-1</sup> )		Fungi ( $10^4$ cfu g <sup>-1</sup> )		Actinomycetes ( $10^5$ cfu g <sup>-1</sup> )	
	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>
<b>M-Establishment methods</b>						
<b>M<sub>1</sub></b>	68.2 <sup>a</sup>	71.8 <sup>a</sup>	33.9 <sup>a</sup>	37.1 <sup>a</sup>	20.0 <sup>a</sup>	21.4 <sup>a</sup>
<b>M<sub>2</sub></b>	67.1 <sup>b</sup>	70.8 <sup>b</sup>	32.9 <sup>b</sup>	36.1 <sup>b</sup>	19.6 <sup>b</sup>	21.0 <sup>b</sup>
<b>M<sub>3</sub></b>	66.1 <sup>b</sup>	69.9 <sup>b</sup>	32.1 <sup>b</sup>	35.2 <sup>b</sup>	19.0 <sup>b</sup>	20.4 <sup>b</sup>
<b>SEd</b>	1.90	2.01	0.94	1.03	0.55	0.59
<b>CD(P=0.05)</b>	3.58	4.25	1.98	2.17	1.17	1.25
<b>S- Nutrient management practices</b>						
<b>S<sub>1</sub></b>	59.3 <sup>c</sup>	64.0 <sup>c</sup>	27.0 <sup>c</sup>	30.2 <sup>c</sup>	16.1 <sup>c</sup>	17.5 <sup>c</sup>
<b>S<sub>2</sub></b>	63.4 <sup>a</sup>	68.0 <sup>a</sup>	29.7 <sup>a</sup>	32.9 <sup>a</sup>	18.7 <sup>a</sup>	20.0 <sup>a</sup>
<b>S<sub>3</sub></b>	67.1 <sup>b</sup>	71.8 <sup>b</sup>	33.4 <sup>b</sup>	36.6 <sup>b</sup>	20.1 <sup>b</sup>	21.4 <sup>b</sup>
<b>S<sub>4</sub></b>	70.5 <sup>c</sup>	75.2 <sup>c</sup>	36.5 <sup>c</sup>	39.6 <sup>c</sup>	21.5 <sup>c</sup>	22.7 <sup>c</sup>
<b>S<sub>5</sub></b>	72.9 <sup>d</sup>	77.6 <sup>d</sup>	38.9 <sup>d</sup>	42.2 <sup>d</sup>	22.7 <sup>d</sup>	24.2 <sup>d</sup>
<b>S<sub>6</sub></b>	75.2 <sup>e</sup>	79.9 <sup>e</sup>	41.2 <sup>e</sup>	44.6 <sup>e</sup>	24.1 <sup>e</sup>	25.4 <sup>e</sup>
<b>S<sub>7</sub></b>	54.7 <sup>f</sup>	59.4 <sup>f</sup>	24.0 <sup>f</sup>	26.9 <sup>f</sup>	13.6 <sup>f</sup>	15.0 <sup>f</sup>
<b>SEd</b>	1.79	1.92	0.90	0.98	0.52	0.56
<b>CD(P=0.05)</b>	3.90	4.18	1.96	2.15	1.13	1.21
<b>M x S (Interaction effect)</b>						
<b>M<sub>1</sub>S<sub>1</sub></b>	59.1 <sup>c</sup>	64.6 <sup>c</sup>	28.1 <sup>c</sup>	31.3 <sup>c</sup>	16.9 <sup>c</sup>	18.4 <sup>c</sup>
<b>M<sub>1</sub>S<sub>2</sub></b>	61.8 <sup>a</sup>	69.6 <sup>a</sup>	30.9 <sup>a</sup>	34.1 <sup>a</sup>	19.2 <sup>a</sup>	20.5 <sup>a</sup>
<b>M<sub>1</sub>S<sub>3</sub></b>	66.1 <sup>b</sup>	73.7 <sup>b</sup>	34.3 <sup>b</sup>	37.5 <sup>b</sup>	20.6 <sup>b</sup>	21.9 <sup>b</sup>
<b>M<sub>1</sub>S<sub>4</sub></b>	69.6 <sup>c</sup>	76.3 <sup>c</sup>	37.5 <sup>c</sup>	40.7 <sup>c</sup>	21.9 <sup>c</sup>	23.2 <sup>c</sup>
<b>M<sub>1</sub>S<sub>5</sub></b>	72.6 <sup>d</sup>	77.2 <sup>d</sup>	39.8 <sup>d</sup>	43.5 <sup>d</sup>	23.2 <sup>d</sup>	24.6 <sup>d</sup>
<b>M<sub>1</sub>S<sub>6</sub></b>	74.8 <sup>e</sup>	80.7 <sup>e</sup>	41.9 <sup>e</sup>	45.1 <sup>e</sup>	24.6 <sup>e</sup>	25.9 <sup>e</sup>
<b>M<sub>1</sub>S<sub>7</sub></b>	52.8 <sup>f</sup>	60.7 <sup>f</sup>	24.6 <sup>f</sup>	27.9 <sup>f</sup>	14.0 <sup>f</sup>	15.2 <sup>f</sup>
<b>M<sub>2</sub>S<sub>1</sub></b>	59.9 <sup>d</sup>	63.6 <sup>d</sup>	27.1 <sup>d</sup>	30.3 <sup>d</sup>	16.4 <sup>d</sup>	17.8 <sup>d</sup>
<b>M<sub>2</sub>S<sub>2</sub></b>	64.9 <sup>a</sup>	68.0 <sup>a</sup>	29.7 <sup>a</sup>	32.9 <sup>a</sup>	18.7 <sup>a</sup>	20.1 <sup>a</sup>
<b>M<sub>2</sub>S<sub>3</sub></b>	69.0 <sup>b</sup>	70.9 <sup>b</sup>	33.7 <sup>b</sup>	36.9 <sup>b</sup>	20.2 <sup>b</sup>	21.5 <sup>b</sup>
<b>M<sub>2</sub>S<sub>4</sub></b>	71.6 <sup>c</sup>	75.1 <sup>c</sup>	36.4 <sup>c</sup>	39.6 <sup>c</sup>	21.5 <sup>c</sup>	22.7 <sup>c</sup>
<b>M<sub>2</sub>S<sub>5</sub></b>	72.5 <sup>d</sup>	78.3 <sup>d</sup>	38.7 <sup>d</sup>	41.9 <sup>d</sup>	22.7 <sup>d</sup>	24.2 <sup>d</sup>
<b>M<sub>2</sub>S<sub>6</sub></b>	76.0 <sup>e</sup>	79.6 <sup>e</sup>	41.2 <sup>e</sup>	44.9 <sup>e</sup>	24.1 <sup>e</sup>	25.5 <sup>e</sup>
<b>M<sub>2</sub>S<sub>7</sub></b>	56.0 <sup>f</sup>	60.1 <sup>f</sup>	23.7 <sup>f</sup>	26.5 <sup>f</sup>	13.5 <sup>f</sup>	15.0 <sup>f</sup>
<b>M<sub>3</sub>S<sub>1</sub></b>	58.9 <sup>c</sup>	63.8 <sup>c</sup>	25.9 <sup>c</sup>	29.1 <sup>c</sup>	15.1 <sup>c</sup>	16.3 <sup>c</sup>
<b>M<sub>3</sub>S<sub>2</sub></b>	63.3 <sup>a</sup>	66.5 <sup>a</sup>	28.5 <sup>a</sup>	31.7 <sup>a</sup>	18.2 <sup>a</sup>	19.6 <sup>a</sup>
<b>M<sub>3</sub>S<sub>3</sub></b>	66.2 <sup>b</sup>	70.8 <sup>b</sup>	32.2 <sup>b</sup>	35.4 <sup>b</sup>	19.6 <sup>b</sup>	20.8 <sup>b</sup>
<b>M<sub>3</sub>S<sub>4</sub></b>	70.4 <sup>c</sup>	74.3 <sup>c</sup>	35.5 <sup>c</sup>	38.7 <sup>c</sup>	21.0 <sup>c</sup>	22.3 <sup>c</sup>
<b>M<sub>3</sub>S<sub>5</sub></b>	73.6 <sup>d</sup>	77.3 <sup>d</sup>	38.1 <sup>d</sup>	41.3 <sup>d</sup>	22.3 <sup>d</sup>	23.8 <sup>d</sup>
<b>M<sub>3</sub>S<sub>6</sub></b>	74.9 <sup>e</sup>	79.5 <sup>e</sup>	40.6 <sup>e</sup>	43.8 <sup>e</sup>	23.7 <sup>e</sup>	24.9 <sup>e</sup>
<b>M<sub>3</sub>S<sub>7</sub></b>	55.4 <sup>f</sup>	57.5 <sup>f</sup>	23.7 <sup>f</sup>	26.4 <sup>f</sup>	13.2 <sup>f</sup>	14.8 <sup>f</sup>
<b>SEd</b>	1.80	1.93	0.92	1.00	0.53	0.57
<b>CD(P=0.05)</b>	3.86	4.15	1.97	2.15	1.13	1.22

Means followed by the same letter do not differ statistically among themselves by Duncan's multiple range test, ( $p \leq 0.05$ ).

SEd: Standard Error of Difference between means. CD: Critical Difference at a 5 % significance level

M1-Mechanical Transplanting, M2-Transplanting under saturated soil condition, M3-Conventional Transplanting. S1 -Blanket recommendation given by ICAR for basmati, S2- STCR recommendation, S3 -75 % Inorganic + 25 % Organic as N equivalent, S4 -50 % Inorganic + 50 % Organic as N equivalent, S5 -25 % Inorganic + 75 % Organic as N equivalent, S6 -100 % Organic as N equivalent, S7 -Absolute control.

nutrient management, the application of 100 % organic as N equivalent (S<sub>6</sub>) recorded the maximum actinomycetes population of ( $24.1$  and  $25.4 \times 10^5$  cfu g<sup>-1</sup>) during both the seasons. Absolute control (S<sub>7</sub>), on the other hand, recorded the lowest actinomycetes population of ( $13.6 \times 10^5$  cfu g<sup>-1</sup> and  $15.0 \times 10^5$  cfu g<sup>-1</sup>) during the respective seasons. The interaction between establishment methods and nutrient management practices showed that, mechanical transplanting with 100 % organic as N equivalent (M<sub>1</sub>S<sub>6</sub>) recorded the highest actinomycetes population of ( $24.6 \times 10^5$  cfu g<sup>-1</sup> and  $25.9 \times 10^5$  cfu g<sup>-1</sup>) during *rabi* and *kharif* seasons respectively. Conversely, conventional transplanting combined with absolute control (M<sub>3</sub>S<sub>7</sub>) accounted the lowest population of ( $13.2 \times 10^5$  cfu g<sup>-1</sup> and  $14.8 \times 10^5$  cfu g<sup>-1</sup>) across the two seasons.

### Soil enzyme activity

Urease, dehydrogenase and phosphatase activities are vital indicators of soil health and fertility, reflecting the biological and biochemical processes within the soil ecosystem. These

enzymes play a key role in nutrient cycling by facilitating the breakdown and transformation of essential nutrients. Their activity levels are strongly influenced by nutrient management practices and methods of crop establishment, highlighting their responsiveness to soil inputs and environmental conditions. The integration of efficient nutrient management strategies significantly enhanced the activity of these enzymes, thereby improving nutrient availability and soil productivity. Moreover, urease, dehydrogenase and phosphatase activities showed notable variations depending on the establishment methods and nutrient management approaches employed. Soil enzyme activities were greatly influenced by both establishment methods and nutrient management practices over the two seasons in basmati rice.

### Urease activity

Urease activity is a key biochemical indicator that reflects the soil's ability to hydrolyse urea into NH<sub>3</sub>, facilitating nitrogen availability for plant uptake. It is driven by microbial activity

and is highly responsive to soil management practices and nutrient inputs. Enhanced urease activity supports efficient nitrogen cycling, contributing to improved soil fertility and crop growth.

Mechanical transplanting ( $M_1$ ) showed the highest urease activity ( $28.1 \mu\text{g NH}_4\text{-N g}^{-1}\text{soil day}^{-1}$  in *rabi*;  $30.4 \mu\text{g NH}_4\text{-N g}^{-1}\text{soil day}^{-1}$  in *kharif*) (Table 3). The next highest was recorded under transplanting under saturated soil conditions ( $M_2$ ) with activity of about ( $27.9$  and  $30.1 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ). It was recorded as minimum under conventional transplanting ( $M_3$ ) in both *rabi* ( $27.5 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ) and *kharif* seasons ( $29.8 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ) correspondingly. Regarding nutrient management strategies, application of 100 % organic as N equivalent ( $S_6$ ) recorded maximum urease activity of ( $32.1$  and  $32.3 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ) and was obtained as minimum ( $27.1$  and  $27.3 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ) under absolute control ( $S_7$ ). On interaction, mechanical transplanting with application of 100 % organic as N equivalent ( $M_1S_6$ ) recorded the highest urease

activity ( $30.8$  and  $33.1 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ) compared with the remaining treatment combinations. In disparity, it was found minimum at *rabi* and *kharif* ( $24.8$  and  $27.1 \mu\text{g of NH}_4\text{-N g}^{-1}$  of soil day $^{-1}$ ) seasons under conventional transplanting along with absolute control ( $M_3S_7$ ).

### Dehydrogenase

Dehydrogenase activity serves as a vital indicator of overall microbial activity and soil biological health. This enzyme reflects the oxidative activity of microorganisms, playing a critical role in energy transfer and organic matter decomposition. Dehydrogenase activity is highly sensitive to soil management practices, making it a reliable measure of soil fertility and microbial dynamics.

Across the various establishment methods, mechanical transplanting ( $M_1$ ) recorded the highest dehydrogenase activity of ( $51.4$  and  $54.0 \mu\text{g of TPF g}^{-1}\text{soil day}^{-1}$ ) during both the seasons (Table 3). The next maximum was recorded under transplanting under saturated soil condition ( $M_2$ ). Whereas dehydrogenase activity was recorded

**Table 3.** Effect of establishment methods and nutrient management practices on soil enzyme activities of basmati rice during *rabi* 2023 and *kharif* 2024

Treatment	Urease		Dehydrogenase		Phosphatase	
	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>
<b>M-Establishment methods</b>						
$M_1$	28.1 <sup>a</sup>	30.4 <sup>a</sup>	51.4 <sup>a</sup>	54.0 <sup>a</sup>	44.5 <sup>a</sup>	47.9 <sup>a</sup>
$M_2$	27.9 <sup>b</sup>	30.1 <sup>b</sup>	50.4 <sup>b</sup>	53.2 <sup>b</sup>	43.6 <sup>b</sup>	47.0 <sup>b</sup>
$M_3$	27.5 <sup>b</sup>	29.8 <sup>b</sup>	49.5 <sup>b</sup>	52.3 <sup>b</sup>	42.0 <sup>b</sup>	45.6 <sup>b</sup>
SEd	0.79	0.86	1.23	1.33	1.43	1.51
CD(P=0.05)	1.67	1.81	2.60	2.81	3.03	3.19
<b>S- Nutrient management practices</b>						
$S_1$	28.1 <sup>c</sup>	28.2 <sup>c</sup>	45.7 <sup>c</sup>	48.3 <sup>c</sup>	38.4 <sup>c</sup>	41.8 <sup>c</sup>
$S_2$	29.2 <sup>a</sup>	29.3 <sup>a</sup>	48.0 <sup>a</sup>	50.6 <sup>a</sup>	40.9 <sup>a</sup>	44.3 <sup>a</sup>
$S_3$	30.2 <sup>b</sup>	30.4 <sup>b</sup>	50.1 <sup>b</sup>	52.7 <sup>b</sup>	43.4 <sup>b</sup>	46.8 <sup>b</sup>
$S_4$	30.7 <sup>c</sup>	30.7 <sup>c</sup>	51.9 <sup>c</sup>	54.6 <sup>c</sup>	46.2 <sup>c</sup>	49.5 <sup>c</sup>
$S_5$	31.4 <sup>d</sup>	31.4 <sup>d</sup>	55.4 <sup>d</sup>	58.1 <sup>d</sup>	48.4 <sup>d</sup>	51.8 <sup>d</sup>
$S_6$	32.1 <sup>e</sup>	32.3 <sup>e</sup>	58.4 <sup>e</sup>	61.1 <sup>e</sup>	51.6 <sup>e</sup>	55.2 <sup>e</sup>
$S_7$	27.1 <sup>f</sup>	27.3 <sup>f</sup>	43.6 <sup>f</sup>	46.7 <sup>f</sup>	34.6 <sup>f</sup>	38.5 <sup>f</sup>
SEd	0.81	0.82	1.19	1.29	1.40	1.48
CD(P=0.05)	1.78	1.79	2.59	2.81	3.06	3.23
<b>M x S (Interaction effect)</b>						
$M_1S_1$	26.4 <sup>c</sup>	28.7 <sup>c</sup>	46.2 <sup>c</sup>	48.8 <sup>c</sup>	39.2 <sup>c</sup>	42.6 <sup>c</sup>
$M_1S_2$	27.6 <sup>a</sup>	29.8 <sup>a</sup>	48.7 <sup>a</sup>	51.3 <sup>a</sup>	41.8 <sup>a</sup>	45.2 <sup>a</sup>
$M_1S_3$	28.1 <sup>b</sup>	30.4 <sup>b</sup>	50.7 <sup>b</sup>	53.3 <sup>b</sup>	44.2 <sup>b</sup>	47.6 <sup>b</sup>
$M_1S_4$	28.8 <sup>c</sup>	31.2 <sup>c</sup>	53.0 <sup>c</sup>	55.7 <sup>c</sup>	46.8 <sup>c</sup>	50.1 <sup>c</sup>
$M_1S_5$	29.7 <sup>d</sup>	32.0 <sup>d</sup>	56.6 <sup>d</sup>	59.4 <sup>d</sup>	49.6 <sup>d</sup>	53.0 <sup>d</sup>
$M_1S_6$	30.8 <sup>e</sup>	33.1 <sup>e</sup>	59.8 <sup>e</sup>	62.4 <sup>e</sup>	53.1 <sup>e</sup>	56.4 <sup>e</sup>
$M_1S_7$	25.6 <sup>f</sup>	27.8 <sup>f</sup>	44.7 <sup>f</sup>	47.3 <sup>f</sup>	36.9 <sup>f</sup>	40.4 <sup>f</sup>
$M_2S_1$	26.1 <sup>d</sup>	28.3 <sup>d</sup>	45.7 <sup>d</sup>	48.4 <sup>d</sup>	38.4 <sup>d</sup>	41.7 <sup>d</sup>
$M_2S_2$	27.2 <sup>a</sup>	29.5 <sup>a</sup>	47.9 <sup>a</sup>	50.6 <sup>a</sup>	41.1 <sup>a</sup>	44.5 <sup>a</sup>
$M_2S_3$	28.2 <sup>b</sup>	30.4 <sup>b</sup>	50.1 <sup>b</sup>	52.8 <sup>b</sup>	43.4 <sup>b</sup>	46.6 <sup>b</sup>
$M_2S_4$	28.7 <sup>c</sup>	31.0 <sup>c</sup>	51.7 <sup>c</sup>	54.4 <sup>c</sup>	46.3 <sup>c</sup>	49.7 <sup>c</sup>
$M_2S_5$	29.5 <sup>d</sup>	31.8 <sup>d</sup>	55.6 <sup>d</sup>	58.3 <sup>d</sup>	48.2 <sup>d</sup>	51.6 <sup>d</sup>
$M_2S_6$	30.4 <sup>e</sup>	32.6 <sup>e</sup>	58.2 <sup>e</sup>	60.8 <sup>e</sup>	51.6 <sup>e</sup>	55.2 <sup>e</sup>
$M_2S_7$	25.1 <sup>f</sup>	27.4 <sup>f</sup>	43.6 <sup>f</sup>	46.9 <sup>f</sup>	36.2 <sup>f</sup>	39.6 <sup>f</sup>
$M_3S_1$	25.8 <sup>c</sup>	28.1 <sup>c</sup>	45.2 <sup>c</sup>	47.7 <sup>c</sup>	37.6 <sup>c</sup>	41.1 <sup>c</sup>
$M_3S_2$	26.9 <sup>a</sup>	29.2 <sup>a</sup>	47.4 <sup>a</sup>	50.1 <sup>a</sup>	39.8 <sup>a</sup>	43.2 <sup>a</sup>
$M_3S_3$	27.9 <sup>b</sup>	30.2 <sup>b</sup>	49.4 <sup>b</sup>	52.2 <sup>b</sup>	42.8 <sup>b</sup>	46.1 <sup>b</sup>
$M_3S_4$	28.4 <sup>c</sup>	30.7 <sup>c</sup>	51.1 <sup>c</sup>	53.8 <sup>c</sup>	45.5 <sup>c</sup>	48.8 <sup>c</sup>
$M_3S_5$	29.1 <sup>d</sup>	31.4 <sup>d</sup>	53.9 <sup>d</sup>	56.6 <sup>d</sup>	47.3 <sup>d</sup>	50.7 <sup>d</sup>
$M_3S_6$	29.8 <sup>e</sup>	32.1 <sup>e</sup>	57.3 <sup>e</sup>	60.0 <sup>e</sup>	50.2 <sup>e</sup>	53.9 <sup>e</sup>
$M_3S_7$	24.8 <sup>f</sup>	27.1 <sup>f</sup>	42.6 <sup>f</sup>	46.0 <sup>f</sup>	30.6 <sup>f</sup>	35.5 <sup>f</sup>
SEd	0.78	0.84	1.17	1.28	1.43	1.51
CD(P=0.05)	1.67	1.81	2.51	2.76	3.07	3.25

Means followed by the same letter do not differ statistically among themselves by Duncan's multiple range test, ( $p \leq 0.05$ ).

SEd: Standard Error of Difference between means. CD: Critical Difference at a 5 % significance level

$M_1$ -Mechanical Transplanting,  $M_2$ -Transplanting under saturated soil condition,  $M_3$ -Conventional Transplanting.  $S_1$  -Blanket recommendation given by ICAR for basmati,  $S_2$ - STCR recommendation,  $S_3$  -75 % Inorganic + 25 % Organic as N equivalent,  $S_4$  -50 % Inorganic + 50 % Organic as N equivalent,  $S_5$  -25 % Inorganic + 75 % Organic as N equivalent,  $S_6$  -100 % Organic as N equivalent,  $S_7$  -Absolute control.

minimum with conventional transplanting ( $M_3$ ) during *rabi* ( $49.5 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) and *kharif* seasons ( $52.3 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) individually. Regarding nutrient management strategies, application of 100 % of organic as N equivalent ( $S_6$ ) recorded maximum dehydrogenase activity ( $58.4$  and  $61.1 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) and the minimum was recorded ( $43.6$  and  $46.7 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) with absolute control ( $S_7$ ). On interaction, mechanical transplanting with application of 100 % of organic as N equivalent ( $M_1S_6$ ) recorded higher dehydrogenase activity ( $59.8$  and  $62.4 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) during both seasons. In contrast, it was recorded as minimum during *rabi* ( $42.6 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) and *kharif* seasons ( $46.0 \mu\text{g of TPF g}^{-1} \text{ soil day}^{-1}$ ) under conventional transplanting along with absolute control ( $M_3S_7$ ).

### Phosphatase

Phosphatase activity is an essential enzyme indicator that reflects the soil's ability to hydrolyse organic phosphorus compounds into plant available inorganic forms. It plays a crucial role in phosphorus cycling and is influenced by microbial activity, organic matter content and soil management practices. Enhanced phosphatase activity indicates improved phosphorus availability, contributing to better soil fertility and crop productivity.

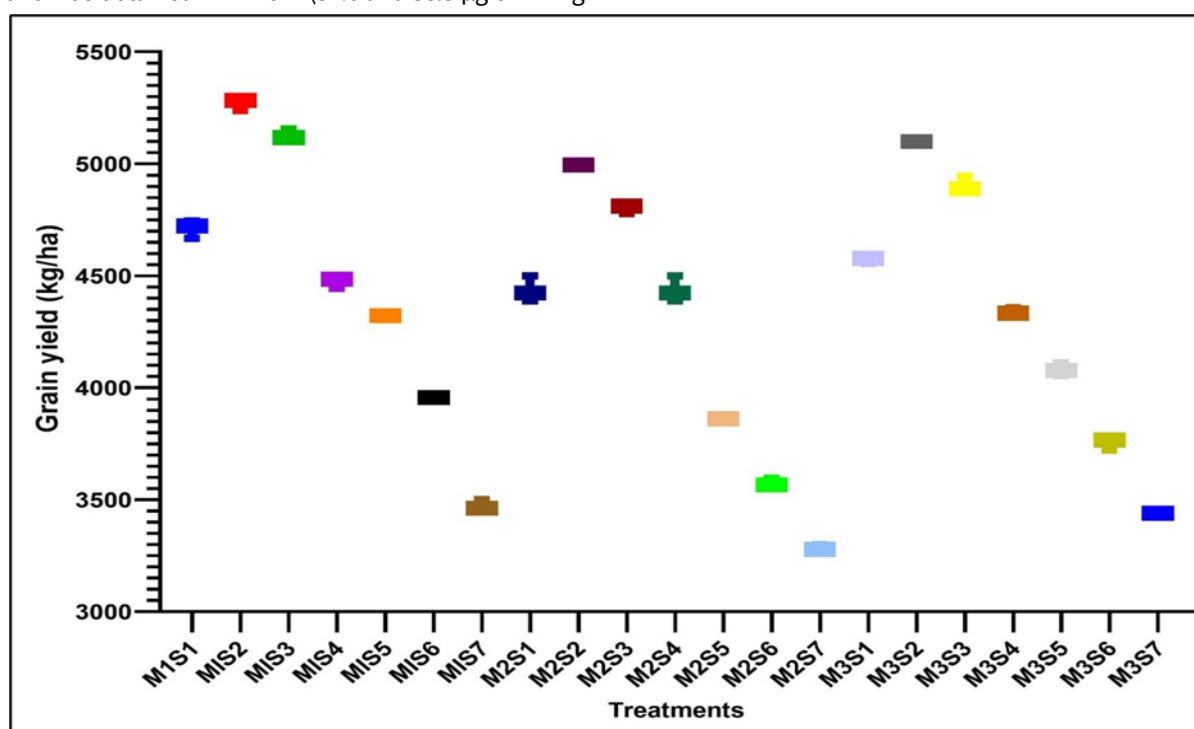
A similar trend was observed for phosphatase activity, as seen with urease and dehydrogenase activities. Mechanical transplanting ( $M_1$ ) accounted maximum phosphatase activity of ( $44.5$  and  $47.9 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) during both the two seasons (Table 3). Next maximum was noted with conventional transplanting ( $M_2$ ) of about ( $43.6$  and  $47.0 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ). It was recorded minimum under transplanting under saturated soil condition ( $M_3$ ) in both *rabi* ( $42.0 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) and *kharif* seasons ( $45.6 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) considerably. 100 % of organic as N equivalent ( $S_6$ ) recorded maximum phosphatase activity ( $51.6$  and  $55.2 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) and was obtained minimum ( $34.6$  and  $38.5 \mu\text{g of PNP g}^{-1}$

soil day<sup>-1</sup>) with absolute control ( $S_7$ ). On interaction, mechanical transplanting with application of 100 % of organic as N equivalent ( $M_1S_6$ ) recorded higher phosphatase activity ( $53.1$  and  $56.4 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) during both seasons. In contrast, it was minimum in both *rabi* ( $30.6 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) and *kharif* ( $35.5 \mu\text{g of PNP g}^{-1} \text{ soil day}^{-1}$ ) under conventional transplanting along with absolute control ( $M_3S_7$ ).

## Discussion

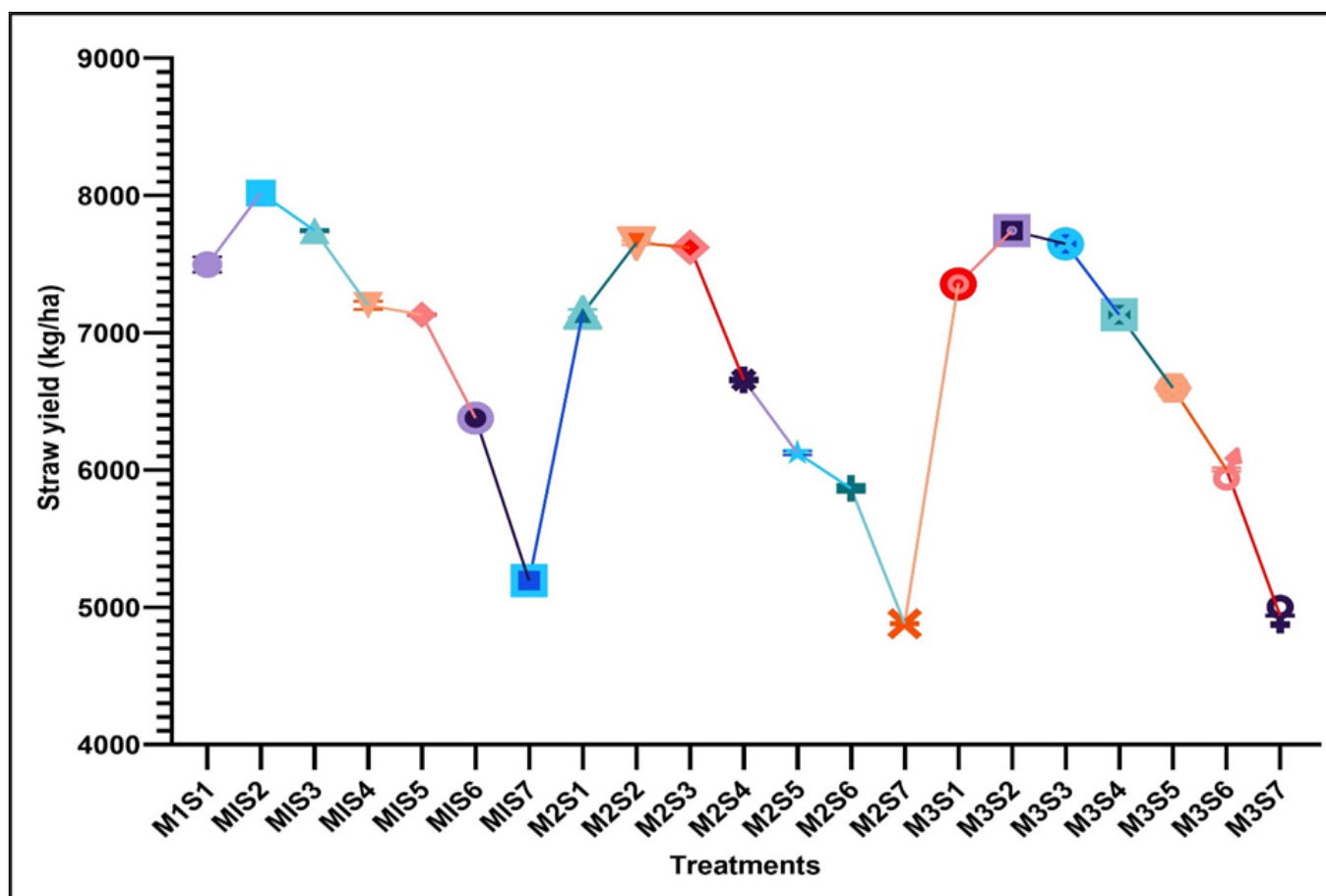
### Yield

Among the establishment methods, higher grain yield and straw yield were observed under mechanical transplanting ( $M_1$ ) (Fig. 3-6). The precise planting depth and optimal spacing associated with mechanical transplanting improved the soil aeration and root proliferation by which created a favourable microenvironment for microbial growth. The increased microbial activity and enzyme production, such as dehydrogenase, urease and phosphatase, enhanced the nutrient mineralization and availability which subsequently improved the nutrient uptake and facilitated efficient translocation of assimilates to the economic parts of the plant, thereby contributing to the higher yield. This is in accordance with earlier findings (24). Concerning nutrient management practices, STCR based nutrient application ( $S_2$ ) recorded the highest grain and straw yields during both seasons. The precise nutrient application enhanced soil fertility and microbial activity in the rhizosphere, promoting the growth of beneficial microbes such as *Rhizobium*, *Azotobacter* and *Bacillus* (nitrogen-fixing bacteria), all of which are responsible for enzymatic activities. These enzymes facilitated nutrient mineralization, making essential nutrients like nitrogen, phosphorus and potassium readily available to the plants. Furthermore, the optimal nutrient supply improved chlorophyll synthesis and photosynthetic

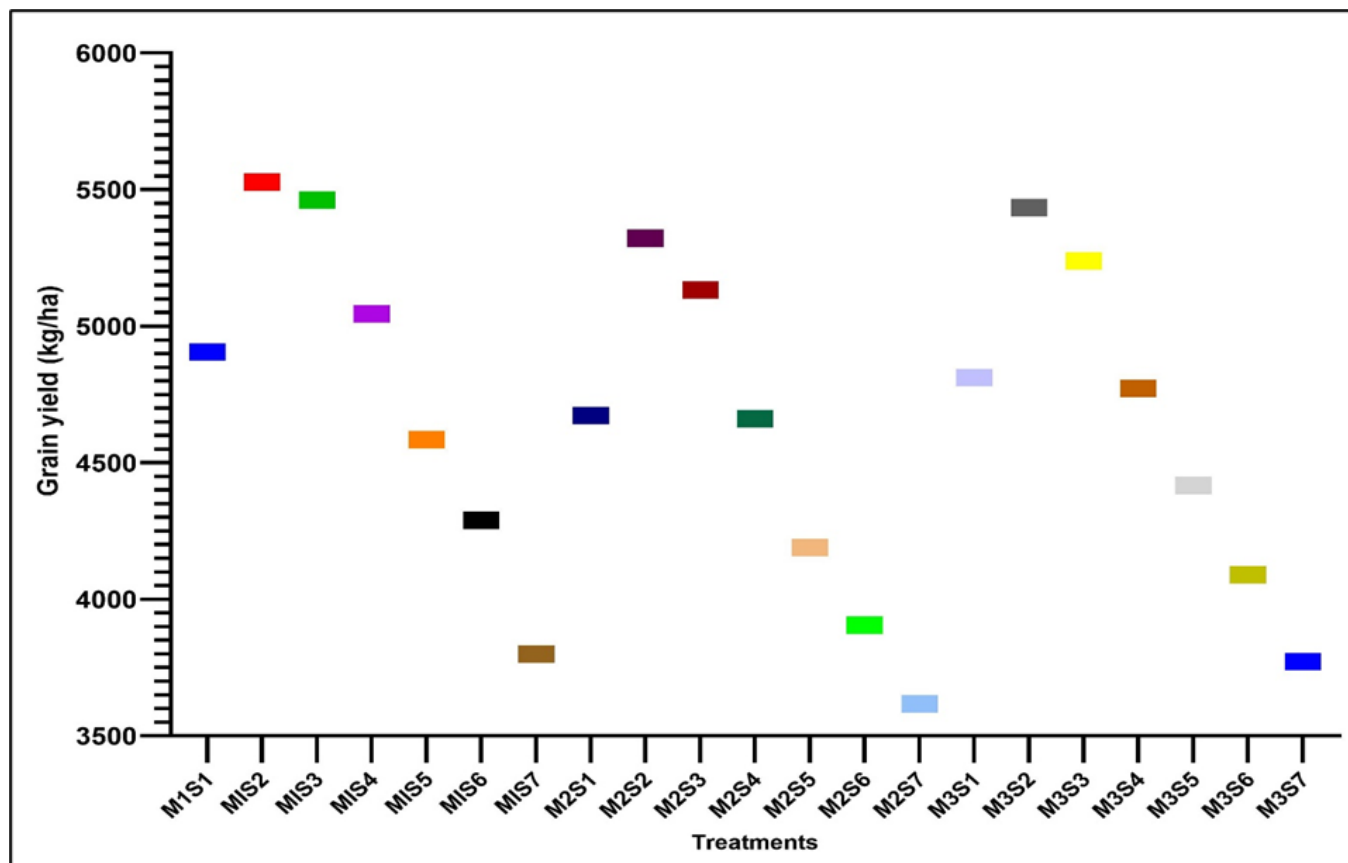


**Fig. 3.** Effect of establishment methods and nutrient management practices on grain yield. (kg ha<sup>-1</sup>) of basmati rice during *rabi* 2023.

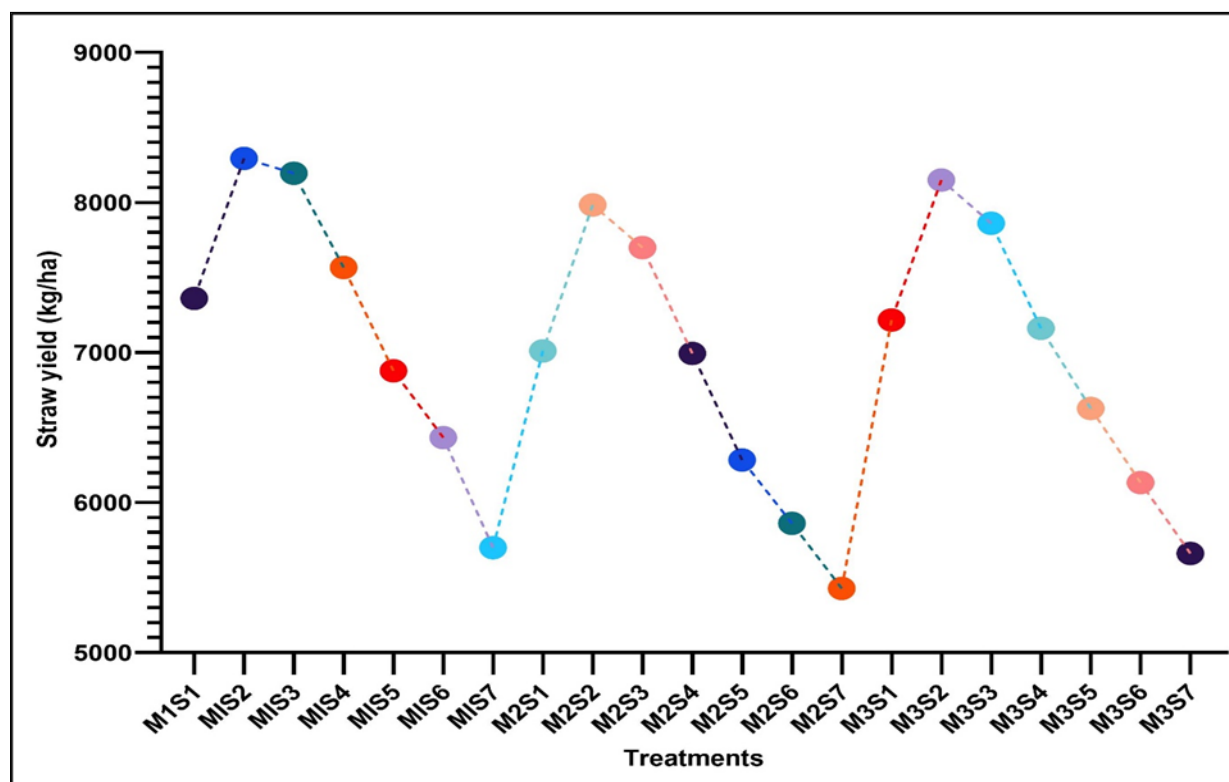




**Fig. 4.** Effect of establishment methods and nutrient management practices on straw yield ( $\text{kg ha}^{-1}$ ) of basmati rice during *rabi* 2023.



**Fig. 5.** Effect of establishment methods and nutrient management practices on grain yield ( $\text{kg ha}^{-1}$ ) of basmati rice during *kharif* 2024.



**Fig. 6.** Effect of establishment methods and nutrient management practices on straw yield ( $\text{kg ha}^{-1}$ ) of basmati rice during *kharif* 2024.

efficiency, leading to better assimilation and translocation of assimilates to the grain and straw. This cumulative effect contributed significantly higher yield under STCR based nutrient application over the other treatments. These findings are in line with earlier reports that also observed enhanced yields under STCR based nutrient management (25).

Regarding the interaction, the combination of mechanical transplanting with STCR based nutrient management ( $M_1S_2$ ) recorded the highest grain and straw yields. This was likely due to the precised planting depth and spacing of mechanical transplanting, which improved root proliferation and soil aeration, created a favourable environment for microbial activity. The STCR based nutrient management ensured a balanced and site-specific nutrient supply, as well enhanced the enzymatic activity and nutrient mineralization. Together, these factors facilitated efficient nutrient uptake and translocation of assimilates to the economic parts, ultimately resulted in higher yield. However, this was on par with mechanical transplanting combined with the application of 75 % inorganic + 25 % organic as N equivalent ( $M_1S_3$ ). This might have been due to the synergistic effect of mechanical transplanting, which enhanced root proliferation and soil aeration and the INM approach, which provided a sustained release of nutrients. In addition, the organic component improved soil structure and microbial activity, while the inorganic component ensured the immediate availability of nutrients. This combination promoted enzymatic activities and facilitated efficient nutrient uptake, as well supported the translocation of assimilates to the economic parts, contributed to comparable yield. Similar findings were reported earlier (26).

### Microbial population

Among the different establishment methods evaluated during both the seasons, mechanical transplanting ( $M_1$ ) recorded a higher microbial population. This could have been attributed to the improved soil aeration and reduced soil compaction resulting from mechanical transplanting. As a result, the mechanical method allowed for better soil structure, which likely facilitated greater oxygen diffusion and root penetration, thereby creating a more conducive environment for microbial proliferation. The results were in close conformity (27). Furthermore, the uniformity in planting depth and spacing achieved through mechanical transplanting might have supported better root development and organic matter deposition in the rhizosphere. This observation aligns with earlier findings that reported a rise in beneficial soil microbial populations under similar conditions (28).

Regarding various nutrient management practices, microbial population was found to be higher under the application of 100 % organics as nitrogen equivalent ( $S_6$ ). This increase could have been attributed to the stimulation of microbial activity by organic compounds such as humic acids, amino acids and polysaccharides that were presented in the organic amendments. Moreover, these compounds not only served as sources of nutrients but also acted as signalling molecules, which promoted microbial proliferation and enhanced metabolic activity. The similar findings were also reported (29). Additionally, organic matter encouraged the development of stable microhabitats within the soil matrix which provided shelter, protection from environmental stress and an ideal environment for microbial colonization and growth. Consequently, the organic nutrient management practice significantly enhanced the soil microbial population compared to other approaches. Similar studies have been

reported earlier (30). Regarding interaction, soil microbial populations were recorded higher under mechanical transplanting with 100 % organic as N equivalent. This might have been due to the enhanced availability of organic substrates, which served as energy sources for microbial growth and activity. The slower nutrient release from organic sources could have also created a favourable environment for sustained microbial proliferation. Additionally, mechanical transplanting might have provided better aeration and root-soil contact, further promoted microbial diversity and abundance. This agrees with previous findings (31).

### Enzyme activity

Similar to microbial populations, enzyme activities also exhibited a comparable trend. The higher level of urease, dehydrogenase and phosphatase activity under mechanical transplanting can be attributed to the reduced soil disturbance after establishment, which allowed microbial populations to stabilize and thrive. The similar findings were reported previously (32). Moreover, the precised planting geometry achieved through mechanical transplanting ensured optimal root-soil interaction which promoted localized enzyme activity through increased root exudates and the decomposition of organic matter in the rhizosphere. These favourable conditions enhanced the biological activity in soil, resulting in higher enzyme production. This is in accordance with earlier findings (33).

Regarding nutrient management practices, higher levels of urease, dehydrogenase and phosphatase were observed under the application of 100 % organic nitrogen equivalent ( $S_6$ ), which was on par with 75 % organic + 25 % inorganic nitrogen equivalent ( $S_5$ ). This may be attributed to the continuous supply of organic substrates, which stimulated microbial activity and enzyme synthesis. In addition, slow decomposition of organic fertilizers released nutrient and organic carbon, which served as energy sources for microbes, thereby enhancing the enzyme production. Similar observations were reported previously (34). Moreover, organic amendments improved soil structure and aeration, which created favourable conditions for microbial growth and activity. As well, the absence of chemical fertilizers reduced stress on soil biota, facilitated increased enzyme expression. Similar findings were reported earlier (35). In contrast, microbial population and enzyme activity were found to be the lowest under absolute control due to the lack of organic inputs. This is in confirmation with the earlier findings (36). Concerning interaction effect, soil enzyme activities were recorded to be higher under mechanical transplanting with 100 % organic nitrogen equivalent. This might have been due to the increased microbial activity associated with the availability of organic matter, which serves as a substrate for enzyme production. The enhanced organic matter content likely supported greater enzymatic breakdown of nutrients, promoting better nutrient cycling and availability in the soil. Additionally, mechanical transplanting might have improved soil structure and aeration, further supported enzyme activity. These findings were accordance with the outcome earlier study (37).

## Conclusion

The results of the study indicated that among the establishment methods, mechanical transplanting ( $M_1$ ) proved to be the most effective. In terms of enhancing soil health, the combination of Mechanical Transplanting with 100 % organic N equivalent ( $M_1S_6$ ) resulted in the highest microbial count and enzyme activity, followed by  $M_1S_5$  (75 % inorganic + 25 % organic). These treatments not only improved microbial diversity but also contributed significantly to soil fertility, making them suitable for long-term soil health and environmental sustainability. However, when considering yield, Mechanical Transplanting with STCR based nutrient management ( $M_1S_2$ ) achieved the highest yield, followed closely by  $M_1S_3$  (75 % inorganic + 25 % organic). While  $M_1S_2$  provided the highest yield, it relied more heavily on inorganic fertilizers, which could impact soil health over time if not carefully managed. For farmers aiming to achieve a balance between high yield and long-term soil health,  $M_1S_6$  or  $M_1S_5$  are recommended, as they foster better microbial activity and soil sustainability. On the other hand, for maximizing immediate yield,  $M_1S_2$  and  $M_1S_3$  are effective, though periodic incorporation of organic practices will help in preserving soil health over the long term.

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## Authors' contributions

VK, RT, PJ and AB were involved in conceptualization, data curation, investigation and methodology. VK also contributed to formal analysis, funding acquisition and software. RT provided supervision. RT, SS and VA provided resources, while RT and VA contributed to visualization. VK, RT, GA, PJ, AB, RS and MB were involved in writing the original draft, as well as reviewing and editing

## Compliance with ethical standards

**Conflict of interest:** There is no conflict of interest.

**Ethical issues:** None

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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