PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9114

eISSN 2348-1900

RESEARCH ARTICLE

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

Vanitha K[1], Ragavan T[1]*, Gurusamy A[1], Prabhakaran J[1], Arthirani B[1], Rani S[1], Somasundaram S[2], Manju Bhargavi[3] & Vasuki A[4]

[1]Department of Agronomy, Agricultural College & Research Institute, Madurai 625 104, Tamil Nadu, India
[2]Department of Agronomy, Cotton Research Station, Veppanthattai 621 116, Tamil Nadu, India
[3]Agricultural Polytechnic, Professor Jayashankar Telangana Agricultural University, Rudrur 503 188, Telangana, India
[4]Department of Crop Management, Mother Terasa College of Agriculture, Pudukkottai 622 102, Tamil Nadu, India

*Correspondence email - ragavan.t@tnau.ac.in

Received: 26 April 2025; Accepted: 14 June 2025; Available online: Version 1.0: 15 July 2025

Cite this article: Vanitha K, Ragavan T, Gurusamy A, Prabhakaran J, Arthirani B, Rani S, Somasundaram S, Manju B, Vasuki A. Effect of establishment methods and nutrient management on soil microbial population, enzyme activity and yield of basmati rice (*Oryza sativa* L.). Plant Science Today (Early Access). https://doi.org/10.14719/pst.9114

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_1), transplanting under saturated soil conditions (M_2) and conventional transplanting (M_3) and seven nutrient management practices in the subplot: ICAR blanket recommendation for basmati (S_1), Soil Test Crop Response (STCR) recommendation (S_2), 75 % inorganic + 25 % organic N equivalent (S_3), 50 % inorganic + 50 % organic N equivalent (S_4), 25 % inorganic + 75 % organic N equivalent (S_5), 100 % organic N equivalent (S_6) and absolute control (S_7). Results revealed that M_1S_6 (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_1S_2) produced the highest yield, followed closely by M_1S_3 (mechanical transplanting with application of 75 % inorganic + 25 % organic as N equivalent), which was statistically on par with M_1S_2. In conclusion, although M_1S_2 achieved the highest yield, M_1S_6 emerged as the most effective for enhancing microbial population and enzyme activity, thereby promoting soil health. M_1S_3 offered a balanced trade-off by achieving high yield while integrating organic nutrients, emphasizing environmental sustainability and soil health. Hence, M_1S_3 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).

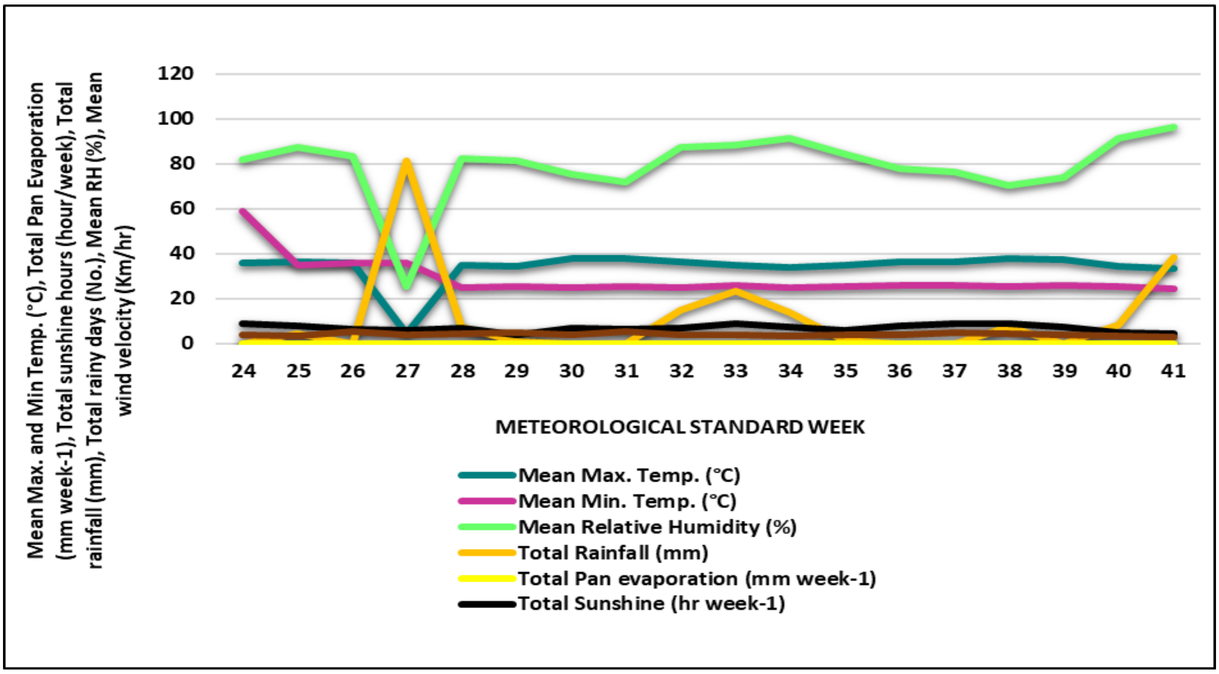

Fig. 1. Weekly weather data during the cropping period of *rabi* 2023

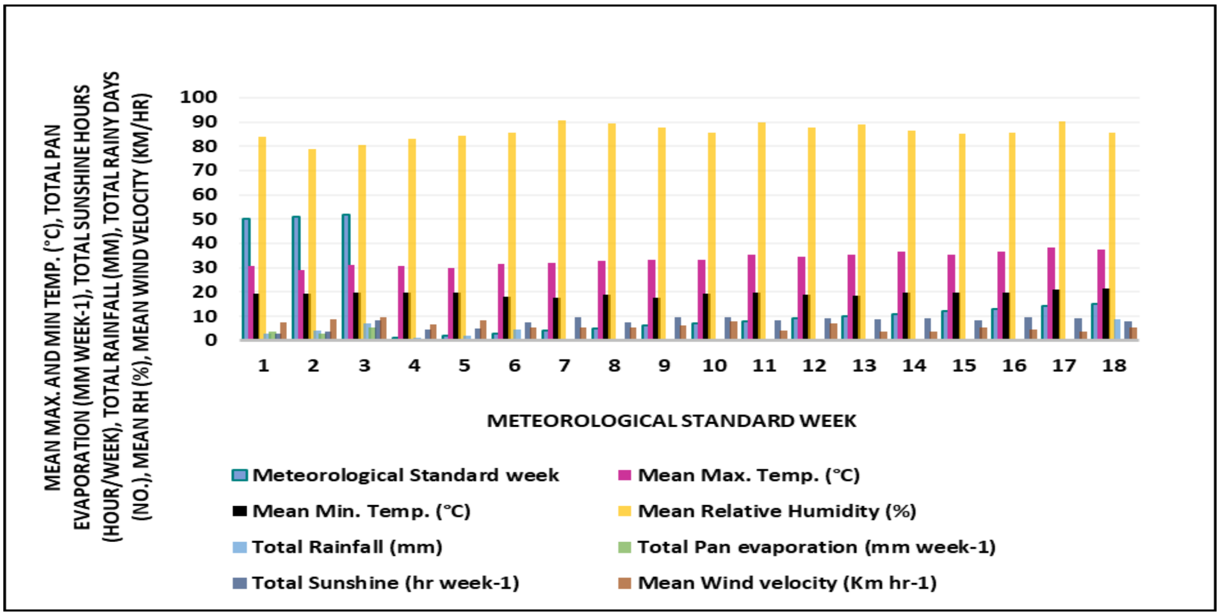

Fig. 2. Weekly weather data during the cropping period of *Kharif* 2024.

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^{-1}), low in available phosphorus (19.5 and 18.9 kg ha^{-1}) and medium in available potassium (284.0 and 272.0 kg ha^{-1}) 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_1), transplanting under saturated soil conditions (M_2) and conventional transplanting (M_3). Whereas, subplots contains seven nutrient management practices, *viz.* blanket recommendation given by ICAR for basmati 90:30:30 kg of NPK ha^{-1} (S_1), STCR recommendation (S_2), 75 % inorganic + 25 % organic as N equivalent (S_3), 50 % inorganic + 50 % organic as N equivalent (S_4), 25 % inorganic + 75 % organic as N equivalent (S_5), 100 % organic as N equivalent (S_6) and absolute control (S_7). 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^{-1}.

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^{-2} dilution. Serial dilutions were prepared up to 10^{-8}. 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^{-8} dilution is used for bacteria, 10^{-5} dilution for actinomycetes and 10^{-4} 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 =

$$\frac{\text{Total number of CFUs x Dilution factor}}{\text{Quantity of soil sample taken on dry weight basis}} \quad \text{(Eqn. 1)}$$

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_3) was then determined through distillation using a micro-Kjeldahl apparatus and the collected NH_3 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_3 released g^{-1} soil day^{-1}.

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 µg of PNP released per gram of soil per day (µg PNP g^{-1} soil 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 µg of TPF released per gram of soil per day (µg TPF g^{-1} soil 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 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 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 kg ha^{-1} during rabi 4801.6 and 7204 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 kg ha^{-1} and straw yields of 6774.3 and 6973 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 kg ha^{-1} and straw yields of 6564.3 and 6751.6 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 kg ha^{-1}) and straw yield of (7806.2 and 8142.6 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 kg ha^{-1}) and straw yields of (5004.9 and 5596.3 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 kg ha^{-1}) and straw yield of (8018.5 and 8294.4 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 kg ha^{-1}) and straw yield of (7744.4 and 8194.4 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 kg ha^{-1}) and straw yield of (4881.5 and 5427.8 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 × 10^7 cfu g^{-1} in *rabi*; 71.8 × 10^7 cfu 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 × 10^7 cfu g^{-1} and 70.8 × 10^7 cfu g^{-1}) during both the seasons. In contrast, the minimum bacterial population was observed under conventional transplanting (M_3), accounting (66.1 × 10^7 and 69.9 × 10^7 cfu 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 × 10^7 and 79.9 × 10^7 cfu g^{-1}) during *rabi* and *kharif* seasons, correspondingly. Conversely, absolute control (S_7) recorded the minimum bacterial population (54.7 × 10^7 and 59.4 × 10^7 cfu 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 × 10^7 and 80.7 × 10^7 cfu g^{-1}) during *rabi* and *kharif* seasons, separately.

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

Treatment	Grain yield (kg ha-1)		Straw yield (kg ha-1)	
	Rabi	*Kharif*	*Rabi*	*Kharif*
M-Establishment methods				
M_1	4476.9a	4801.6a	7023.3a	7204.0a
M_2	4196.8b	4500.0b	6564.3b	6751.6b
M_3	4313.5b	4647.6b	6774.3b	6973.0b
SEd	120.47	127.42	192.18	198.42
CD(P=0.05)	260.21	279.05	407.63	418.67
S- Nutrient management practices				
S_1	4574.1c	4796.3c	7331.5c	7196.3c
S_2	5120.4a	5427.8a	7806.2a	8142.6a
S_3	4944.2b	5277.8b	7671.6b	7918.5b
S_4	4418.5c	4825.9c	6996.3c	7240.7c
S_5	4088.9d	4396.3d	6617.9d	6596.3d
S_6	3761.1e	4094.4e	6082.7e	6142.6e
S_7	3396.3f	3729.6f	5004.9f	5596.3f
SEd	120.52	127.78	177.11	189.07
CD(P=0.05)	255.50	274.78	384.33	412.17
M x S (Interaction effect)				
M_1S_1	4711.1c	4905.6c	7496.3c	7361.1c
M_1S_2	5272.2a	5527.8a	8018.5a	8294.4a
M_1S_3	5127.0b	5461.1b	7744.4b	8194.4b
M_1S_4	4477.8c	5044.4c	7200.0c	7566.7c
M_1S_5	4327.8d	4583.3d	7131.5d	6877.8d
M_1S_6	3955.6e	4288.9e	6377.8e	6433.3e
M_1S_7	3466.7f	3800.0f	5194.4f	5700.0f
M_2S_1	4438.9d	4672.2d	7142.6d	7011.1d
M_2S_2	4988.9a	5322.2a	7655.6a	7983.3a
M_2S_3	4800.0b	5133.3b	7622.2b	7700.0b
M_2S_4	4438.9c	4661.1c	6657.4c	6994.4c
M_2S_5	3855.6d	4188.9d	6124.1d	6283.3d
M_2S_6	3572.2e	3905.6e	5866.7e	5861.1e
M_2S_7	3283.3f	3616.7f	4881.5f	5427.8f
M_3S_1	4572.2c	4811.1c	7355.6c	7216.7c
M_3S_2	5100.0a	5433.3a	7744.4a	8150.0a
M_3S_3	4905.6b	5238.9b	7648.1b	7861.1b
M_3S_4	4338.9c	4772.2c	7131.5c	7161.1c
M_3S_5	4083.3d	4416.7d	6598.1d	6627.8d
M_3S_6	3755.6e	4088.9e	6003.7e	6133.3e
M_3S_7	3438.9f	3772.2f	4938.9f	5661.1f
SEd	119.94	128.19	183.41	191.47
CD(P=0.05)	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_3S_7), which enumerated the values of (52.8×10^7 and 57.5×10^7 cfu g^{-1}) 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_1) showed the highest fungal populations (33.9×10^4 cfu g^{-1} in rabi; 37.1×10^4 cfu g^{-1} in *kharif*) (Table 2). However, it was on par with transplanting under saturated soil condition (M_2) which logged the values of (32.9×10^4 cfu g^{-1} and 36.1×10^4 cfu g^{-1}) over the two seasons. However, the minimum fungal population was noticed under conventional transplanting (M_3) which recorded the values of (32.1×10^4 cfu g^{-1} and 35.2×10^4 cfu g^{-1}) during both the seasons. In terms of nutrient management strategies, 100 % organic as N equivalent (S_6) resulted the highest fungal population (41.2×10^4 cfu g^{-1} and 44.6×10^4 cfu g^{-1}) over the two seasons. Conversely, absolute control (S_7) registered the lowest fungal population. The interaction effect revealed that mechanical transplanting with 100 % organic as N equivalent (M_1S_6 10^4 cfu g^{-1}) enumerated the maximum fungal population (41.9×10^4 cfu g^{-1} and 45.1×10^4 cfu g^{-1}) during both the seasons. Whereas, population was observed minimum under conventional transplanting with absolute control (M_3S_7), recorded (23.7×10^4 cfu g^{-1} and 26.4×10^4 cfu g^{-1}) 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_1) recorded the highest actinomycetes population of (20.0×10^5 cfu g^{-1} and 21.4×10^5 cfu g^{-1}) during both the seasons (Table 2). In contrast, the lowest population was observed under conventional transplanting (M_3), which accounted the values of (19.0×10^5 cfu g^{-1} and 20.4×10^5 cfu g^{-1}) 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^{-1})		Fungi (10^4 cfu g^{-1})		Actinomycetes (10^5 cfu g^{-1})	
	Rabi	*Kharif*	*Rabi*	*Kharif*	*Rabi*	*Kharif*
M-Establishment methods						
M_1	68.2^a	71.8^a	33.9^a	37.1^a	20.0^a	21.4^a
M_2	67.1^b	70.8^b	32.9^b	36.1^b	19.6^b	21.0^b
M_3	66.1^b	69.9^b	32.1^b	35.2^b	19.0^b	20.4^b
SEd	1.90	2.01	0.94	1.03	0.55	0.59
CD(P=0.05)	3.58	4.25	1.98	2.17	1.17	1.25
S- Nutrient management practices						
S_1	59.3^c	64.0^c	27.0^c	30.2^c	16.1^c	17.5^c
S_2	63.4^a	68.0^a	29.7^a	32.9^a	18.7^a	20.0^a
S_3	67.1^b	71.8^b	33.4^b	36.6^b	20.1^b	21.4^b
S_4	70.5^c	75.2^c	36.5^c	39.6^c	21.5^c	22.7^c
S_5	72.9^d	77.6^d	38.9^d	42.2^d	22.7^d	24.2^d
S_6	75.2^e	79.9^e	41.2^e	44.6^e	24.1^e	25.4^e
S_7	54.7^f	59.4^f	24.0^f	26.9^f	13.6^f	15.0^f
SEd	1.79	1.92	0.90	0.98	0.52	0.56
CD(P=0.05)	3.90	4.18	1.96	2.15	1.13	1.21
M x S (Interaction effect)						
M_1S_1	59.1^c	64.6^c	28.1^c	31.3^c	16.9^c	18.4^c
M_1S_2	61.8^a	69.6^a	30.9^a	34.1^a	19.2^a	20.5^a
M_1S_3	66.1^b	73.7^b	34.3^b	37.5^b	20.6^b	21.9^b
M_1S_4	69.6^c	76.3^c	37.5^c	40.7^c	21.9^c	23.2^c
M_1S_5	72.6^d	77.2^d	39.8^d	43.5^d	23.2^d	24.6^d
M_1S_6	74.8^e	80.7^e	41.9^e	45.1^e	24.6^e	25.9^e
M_1S_7	52.8^f	60.7^f	24.6^f	27.9^f	14.0^f	15.2^f
M_2S_1	59.9^d	63.6^d	27.1^d	30.3^d	16.4^d	17.8^d
M_2S_2	64.9^a	68.0^a	29.7^a	32.9^a	18.7^a	20.1^a
M_2S_3	69.0^b	70.9^b	33.7^b	36.9^b	20.2^b	21.5^b
M_2S_4	71.6^c	75.1^c	36.4^c	39.6^c	21.5^c	22.7^c
M_2S_5	72.5^d	78.3^d	38.7^d	41.9^d	22.7^d	24.2^d
M_2S_6	76.0^e	79.6^e	41.2^e	44.9^e	24.1^e	25.5^e
M_2S_7	56.0^f	60.1^f	23.7^f	26.5^f	13.5^f	15.0^f
M_3S_1	58.9^c	63.8^c	25.9^c	29.1^c	15.1^c	16.3^c
M_3S_2	63.3^a	66.5^a	28.5^a	31.7^a	18.2^a	19.6^a
M_3S_3	66.2^b	70.8^b	32.2^b	35.4^b	19.6^b	20.8^b
M_3S_4	70.4^c	74.3^c	35.5^c	38.7^c	21.0^c	22.3^c
M_3S_5	73.6^d	77.3^d	38.1^d	41.3^d	22.3^d	23.8^d
M_3S_6	74.9^e	79.5^e	40.6^e	43.8^e	23.7^e	24.9^e
M_3S_7	55.4^f	57.5^f	23.7^f	26.4^f	13.2^f	14.8^f
SEd	1.80	1.93	0.92	1.00	0.53	0.57
CD(P=0.05)	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_6) recorded the maximum actinomycetes population of (24.1 and 25.4 × 10^5cfu g^{-1}) during both the seasons. Absolute control (S_7), on the other hand, recorded the lowest actinomycetes population of (13.6× 10^5cfu g^{-1} and 15.0 × 10^5cfu g^{-1}) during the respective seasons. The interaction between establishment methods and nutrient management practices showed that, mechanical transplanting with 100 % organic as N equivalent (M_1S_6) recorded the highest actinomycetes population of (24.6× 10^5 cfu g^{-1} and 25.9 × 10^5cfu g^{-1}) during *rabi* and *kharif* seasons respectively. Conversely, conventional transplanting combined with absolute control (M_3S_7) accounted the lowest population of (13.2 × 10^5cfu g^{-1} and 14.8 × 10^5cfu g^{-1}) 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_3, 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 µg NH_4-N g^{-1}soil day^{-1} in rabi; 30.4 µg NH_4-N g^{-1} 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 µg of NH_4-N g^{-1} of soil day^{-1}). It was recorded as minimum under conventional transplanting (M_3) in both *rabi* (27.5 µg of NH_4-N $g^{-1}$of soil day^{-1}) and *kharif* seasons (29.8 µg of NH_4-N g^{-1}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 µg of NH_4-N g^{-1} of soil day^{-1}) and was obtained as minimum (27.1 and 27.3 µg of NH_4-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 µg of NH_4-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 µg of NH_4 -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 µg of TPF g^{-1} 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* 2023and *kharif* 2024

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

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.

minimum with conventional transplanting (M_3) during *rabi* (49.5 µg of TPF g^{-1} soil day^{-1}) and *kharif* seasons (52.3 µg of TPF g^{-1}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 µg of TPF g^{-1} soil day^{-1}) and the minimum was recorded (43.6 and 46.7 µg of TPF g^{-1} 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 µg of TPF g^{-1} soil day^{-1}) during both seasons. In contrast, it was recorded as minimum during *rabi* (42.6 µg of TPF g^{-1} soil day^{-1}) and *kharif* seasons (46.0 µg of TPF g^{-1} 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 µg of PNP g^{-1} 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 µg of PNP g^{-1} soil day^{-1}). It was recorded minimum under transplanting under saturated soil condition (M_3) in both *rabi* (42.0 µg of PNP g^{-1} soil day^{-1}) and *kharif* seasons (45.6 µg of PNP g^{-1} soil day^{-1}) considerably. 100 % of organic as N equivalent (S_6) recorded maximum phosphatase activity (51.6 and 55.2 µg of PNP g^{-1} soil day^{-1}) and was obtained minimum (34.6 and 38.5 µg of PNP g^{-1} 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 phosphatase activity (53.1 and 56.4 µg of PNP g^{-1}soil day^{-1}) during both seasons. In contrast, it was minimum in both *rabi* (30.6 µg of PNP g^{-1} soil day^{-1}) and *kharif* (35.5 µg of PNP g^{-1} 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

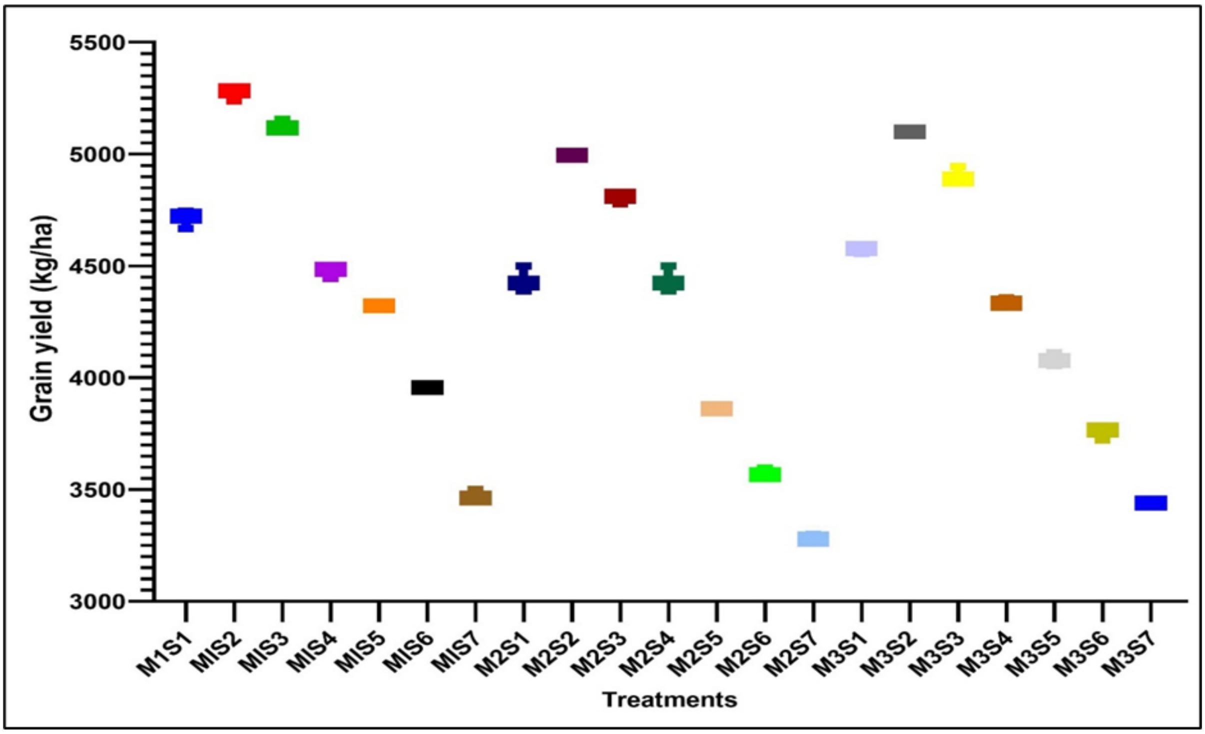

Fig. 3. Effect of establishment methods and nutrient management practices on grain yield.
(kg ha^{-1}) of basmati rice during *rabi* 2023.

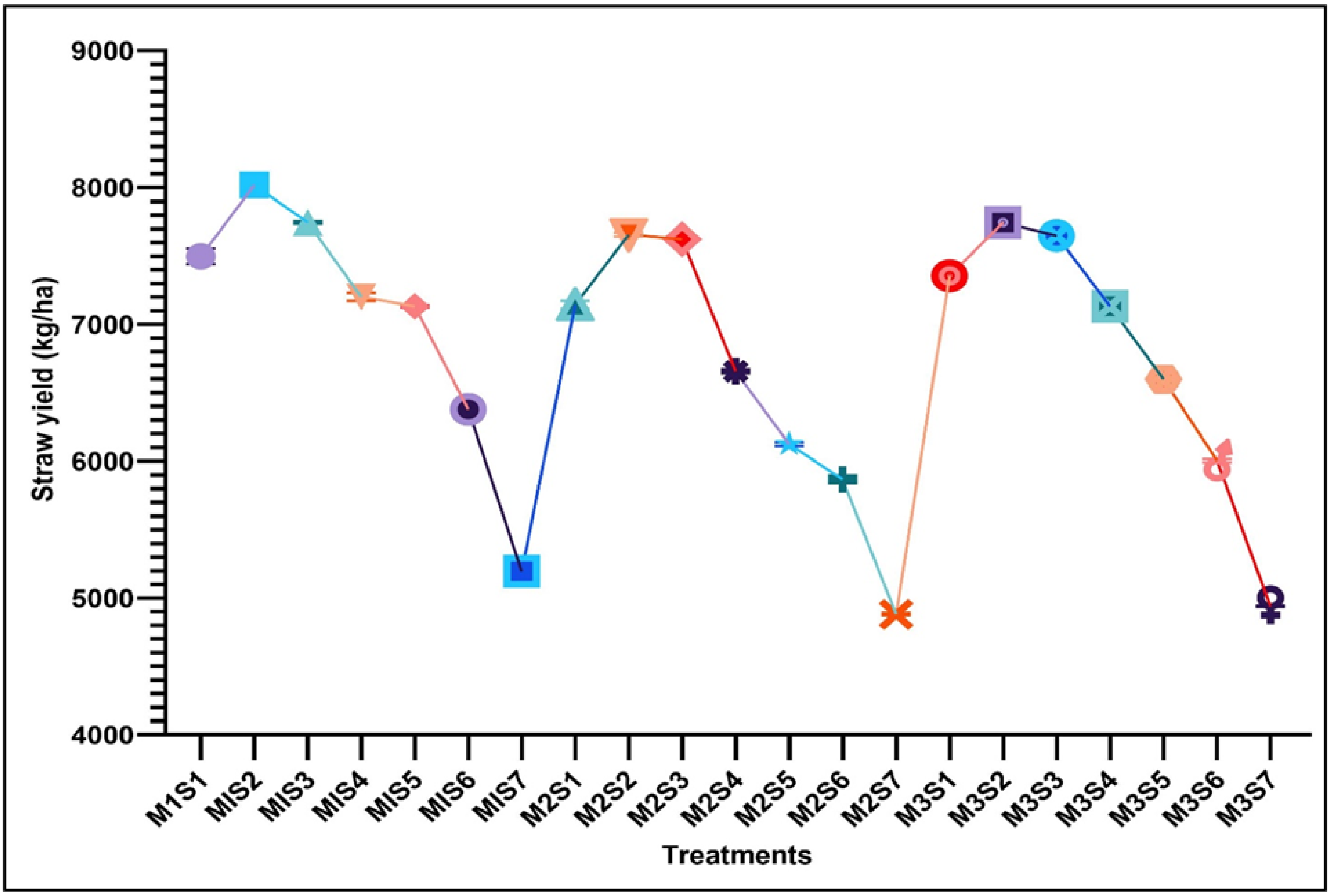

Fig. 4. Effect of establishment methods and nutrient management practices on straw yield (kg ha-[1]) of basmati rice during *rabi* 2023.

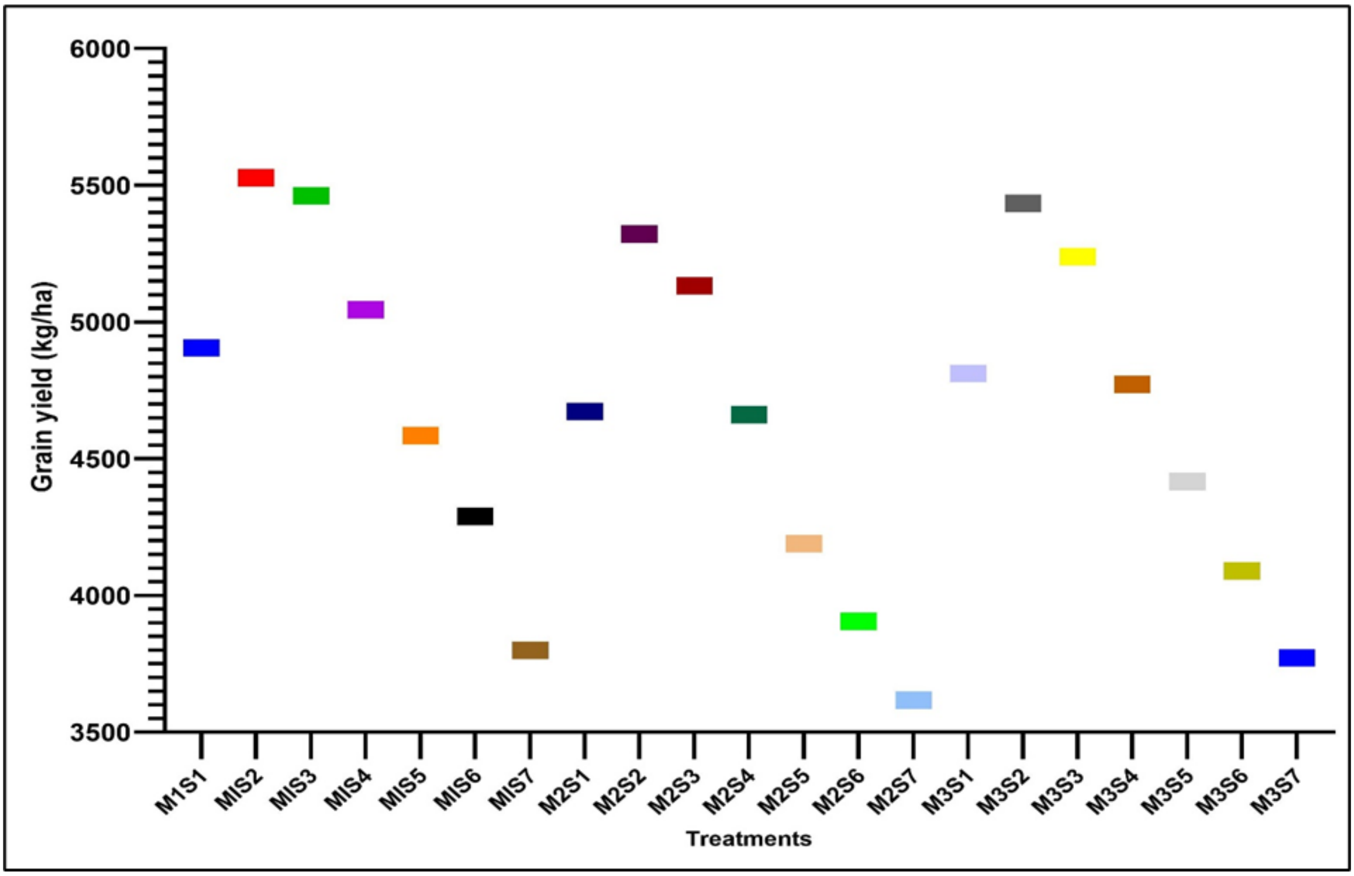

Fig. 5. Effect of establishment methods and nutrient management practices on grain yield (kg ha-[1]) of basmati rice during *kharif* 2024.

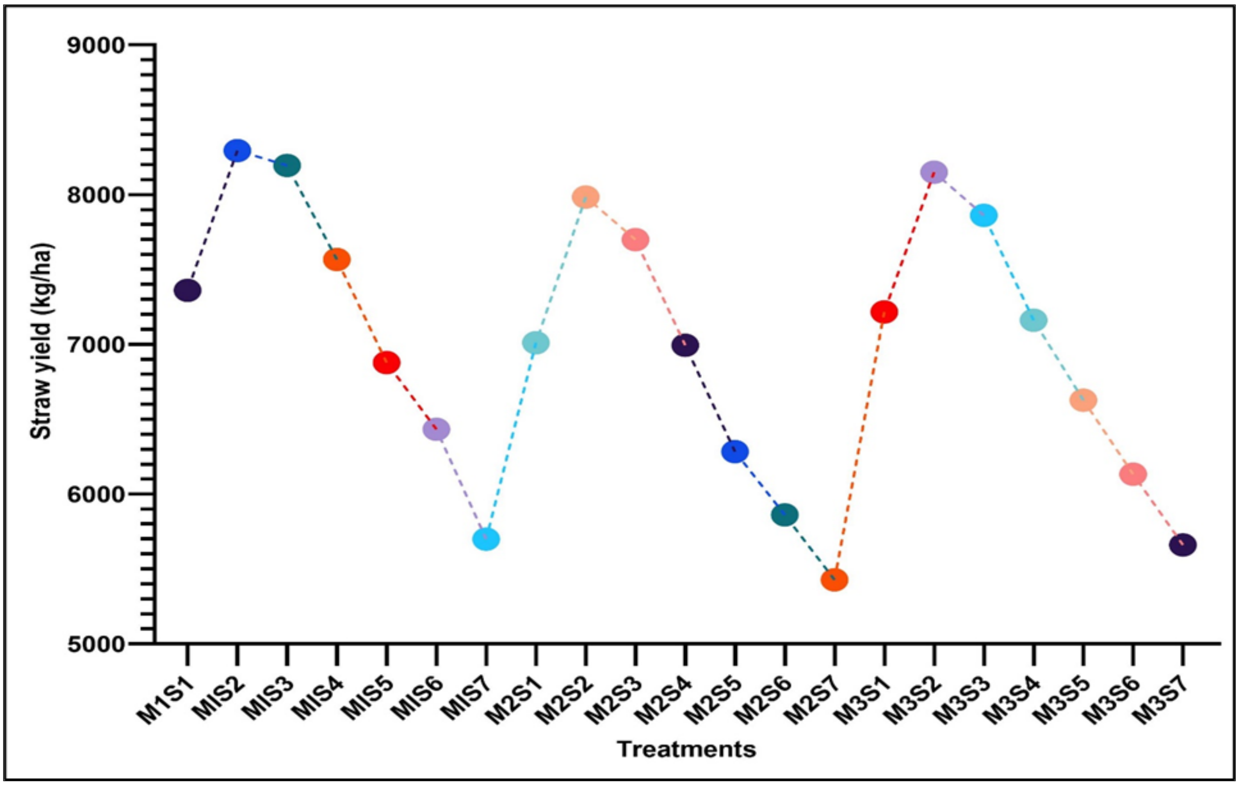

Fig. 6. Effect of establishment methods and nutrient management practices on straw yield (kg ha-[1]) of basmati rice during *kharif* 2024.

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.

Acknowledgements

I would like to express my sincere gratitude to Agriculture College & Research Institute, Madurai for providing access to resources and literature necessary for the completion of this review article.

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.

References

1. Bhagavathi MS, Baradhan G, Suresh Kumar SM, Arivudainambi S. Effect of different crop establishment methods on rice (*Oryza sativa* L.): a review. Plant Arch. 2020;20:3416-22.
2. Aulakh CS, Kaur P, Walia SS, Gill RS, Sharma S, Buttar GS. Productivity and quality of basmati rice (*Oryza sativa*) in relation to nitrogen management. Indian J Agron. 2016;61(4):467-73. https://doi.org/10.31830/2348-7542.2024.ROC1074
3. Gill GK, Gill RS, Sharma N, Brar AS. Effect of transplanting time on the productivity and grain quality of basmati rice. J Agron Crop Sci. 2023;72(4):234-41.
4. Hussain S, Naeem A, Ameen A, Yousuf M, Hussain I, Safdar ME. Impact of planting methods on performance of pk-386 and super basmati at different locations. Pak J Agric Res. 2024;37(4):411-20. https://doi.org/10.17582/journal.pjar/2024/37.4.411.420
5. Rautela S, Bains G, Singh DK, Jahan S, Thi T. Effect of organic, inorganic and integrated nutrient amendments on growth parameters of Basmati rice (*Oryza sativa* L.). Agric Ecosyst Environ. 2022;140:339-53.
6. Rahman A, Salam MA, Kader MA, Islam MS, Perveen S. Growth and yield of boro rice (*Oryza sativa* L.) in response to crop establishment methods and varieties. Arch Agric Environ Sci. 2020;5(2):137-43. https://doi.org/10.26832/24566632.2020.050208
7. Saha R, Patra PS, Ahmed AS. Impact of mechanical transplanting on rice productivity and profitability-review. Int J Econ Plants. 2021;8 (4):226-30. https://doi.org/10.23910/2/2021.0418d
8. Umar M, Ali S, Ali A, Bashir MK, Nawaz N, Khan MH, et al. Adoption of Mechanical Transplanting of Rice (MTR) among rice growers in the rice-zone of Punjab, Pakistan. J Arable Crops Mark. 2022;4(1):21-9. https://doi.org/10.33687/jacm.004.01.4435
9. Setia BP, Moond V, Ninama J, Singh L, Saharan K, Singh AP. Effect of different organic manures and systems of planting on growth and yield of scented rice. Indian J Agric Sci. 2023;110:41-8.
10. Pyngrope D, Mithare P, Ghosh G. Influence of different planting system and levels of nitrogen on growth, yield, quality and economics of rice (*Oryza sativa* L.)-a review. Int J Curr Microbiol Appl Sci. 2019;8(1):2161-72. https://doi.org/10.20546/ijcmas.2019.801.226
11. Aatheeswari R, Suresh S, Ramanathan SP, Jeberlin B. Effect of different integrated nutrient management practices on soil fertility, rice productivity and profitability in Thamirabarani tract of Tamil Nadu. J Pharmacogn Phytochem. 2019;8(4):217-20.
12. Dhaliwal SS, Sharma V, Shukla AK, Verma V, Kaur M, Singh P, et al. Effect of addition of organic manures on basmati yield, nutrient content and soil fertility status in north-western India. Heliyon. 2023;9 (3):e14514. https://doi.org/10.1016/j.heliyon.2023.e14514
13. Nayak R, Paikaray RK, Sahoo TR, Lal MK, Kumar A. Yield, quality and economics of basmati rice as influenced by different organic nutrient management practices. Oryza. 2017;54(1):44-9.
14. Singh S, Singh K, Rao A. Effect of integrated nutrient management on growth and yield of Basmati rice (*Oryza sativa*) through use of different organic manures and crop residues. Crop Res. 2020;55:183-8. https://doi.org/10.31830/2454-1761.2020.027
15. Pandey V, Srivastava A. Effect of integrated use of organic manures and chemical fertilizers under soil test crop response approach on soil properties and yield of maize (*Zea mays* L.). Int J Plant Soil Sci. 2021;33(10):40-7. https://doi.org/10.9734/ijpss/2021/v33i1030471
16. Panigrahi T, Garnayak LM, Ghosh M, Bastia DK, Ghosh DC. Productivity, economics and nutrient use efficiency of basmati rice varieties and its impact on soil fertility under SRI. Int J Biores Stress Manag. 2015;6(3):300-8.
17. Kumar A, Garhwal RS, Kumar S. Influence of organic and inorganic sources of nutrients on soil physicochemical and biological properties under direct-seeded basmati rice. J Indian Soc Soil Sci. 2023;71(3):328-36. https://doi.org/10.5958/0974-0228.2023.00030.0
18. Rajput PS, Srivastava S, Sharma BL, Sachidanand B, Dey P, Aher S B, et al. Effect of soil-test-based long-term fertilization on soil health and performance of rice crop in Vertisols of central India. Int J Agric Environ Biotechnol. 2016;9(5):801-6. https://doi.org/10.5958/2230-732X.2016.00102.9
19. Venkatesh MS, Hazra KK, Ghosh PK, Singh KK. Improving productivity of maize-lentil rotation in alkaline Fluvisol following soil test crop response (STCR)-targeted yield approach of nutrient management. Arch Agron Soil Sci. 2022;68(7):929-43. https://doi.org/10.1080/03650340.2020.1864338
20. Marzouk SH, Kwaslema DR, Omar MM, Mohamed SH. Harnessing the power of soil microbes: their dual impact in integrated nutrient management and mediating climate stress for sustainable rice crop production: a systematic review. Heliyon. 2024. https://doi.org/10.2139/ssrn.4763320
21. Cordero I, Snell H, Bardgett RD. High throughput method for measuring urease activity in soil. Soil Biol Biochem. 2019;134:72-7. https://doi.org/10.1016/j.soilbio.2019.03.014
22. Nannipieri P, Giagnoni L, Landi L, Renella G. Role of phosphatase enzymes in soil. In: Phosphorus in action: biological processes in soil phosphorus cycling. 2011:215-43. https://doi.org/10.1007/978-3-642-15271-9_9
23. Kumar S, Chaudhuri S, Maiti SK. Soil dehydrogenase enzyme activity in natural and mine soil – a review. Middle East J Sci Res. 2013;13 (7):898-906.
24. Alam MK, Bell RW, Hasanuzzaman M, Salahin N, Rashid MH, Akter N, et al. Rice (*Oryza sativa* L.) establishment techniques and their implications for soil properties, global warming potential mitigation and crop yields. Agronomy. 2020;10(6):888. https://doi.org/10.3390/agronomy10060888
25. Kurmi P, Rai HK, Anjna M, Khanam N, Parmar B, Yadav R. Assessment of soil properties under long term integrated nutrient management using STCR-based targeted yield equations under rice-wheat cropping system. Int J Plant Soil Sci. 2022;34(23):562-9. https://doi.org/10.9734/ijpss/2022/v34i232462
26. Midya A, Saren BK, Dey JK, Maitra S, Praharaj S, Gaikwad DJ, et al. Crop establishment methods and integrated nutrient management improve: Part II. Nutrient uptake and use efficiency and soil health in rice (*Oryza sativa* L.) field in the lower Indo-Gangetic plain, India. Agronomy. 2021;11(9):1894. https://doi.org/10.3390/agronomy11091894
27. Padbhushan R, Sharma S, Kumar U, Rana DS, Kohli A, Kaviraj M, et al. Meta-analysis approach to measure the effect of integrated nutrient management on crop performance, microbial activity and carbon stocks in Indian soils. Front Environ Sci. 2021;9:724702. https://doi.org/10.3389/fenvs.2021.724702
28. Darjee S, Singh R, Dhar S, Pandey R, Dwivedi N, Sahu PK, et al. Empirical observation of natural farming inputs on nitrogen uptake, soil health and crop yield of rice-wheat cropping system in the organically managed Inceptisol of Trans Gangetic plain. Front Sustain Food Syst. 2024;8:1324798. https://doi.org/10.3389/fsufs.2024.1324798
29. Verma P, Singh YV, Choudhary AK, Gaind S. Microbial properties of lowland rice soil as affected by nutrient management practices and microbial inoculants. Int J Curr Microbiol Appl Sci. 2017;6(10):3415-9. https://doi.org/10.20546/ijcmas.2017.610.401
30. Kumawat A, Kumar D, Shivay YS, Bhatia A, Rashmi I, Yadav D, et al. Long-term impact of biofertilization on soil health and nutritional quality of organic basmati rice in a typic ustchrept soil of India. Front Environ Sci. 2023;11:1031844.
31. Sharma A, Kachroo D, Hardev Ram RP, Pooja Gupta Soni DJ, Malu Ram Yadav TY. Impact of different transplanting dates and nutrient sources on soil microbial population and grain yield of basmati rice (*Oryza sativa* L.) grown under SRI. Int J Curr Microbiol Appl Sci. 2017;6(3):778-82. https://doi.org/10.20546/ijcmas.2017.603.090

32. Ali A, Liu X, Yang W, Li W, Chen J, Qiao Y, et al. Impact of bio-organic fertilizer incorporation on soil nutrients, enzymatic activity and microbial community in wheat-maize rotation system. Agronomy. 2024;14(9):1942. https://doi.org/10.3390/agronomy14091942
33. Sheoran S, Prakash D, Yadav PK, Gupta RK, Al-Ansari N, El-Hendawy S, et al. Long-term application of FYM and fertilizer N improve soil fertility and enzyme activity in 51st wheat cycle under pearl millet-wheat. Sci Rep. 2024;14(1):21695. https://doi.org/10.1038/s41598-024-72076-w
34. Chatterjee D, Nayak AK, Mishra A, Swain CK, Kumar U, Bhaduri D, et al. Effect of long-term organic fertilization in flooded rice soil on phosphorus transformation and phosphate solubilizing microorganisms. J Soil Sci Plant Nutr. 2021;21:1368-81. https://doi.org/10.1007/s42729-021-00446-8
35. Basha SJ, Basavarajappa R, Shimalli G, Babalad HB. Soil microbial dynamics and enzyme activities as influenced by organic and inorganic nutrient management in vertisols under aerobic rice cultivation. J Environ Biol. 2017;38(1):131. https://doi.org/10.22438/jeb/38/1/MS-205
36. Yadav S, Lal M, Naresh RK, Yadav RB, Yadav AK, Yadav KG, et al. Effect of organic and inorganic nutrient sources on productivity, grain quality of rice and soil health in north-west IGP: a review. Int J Curr Microbiol Appl Sci. 2019;8(12):2488-514. https://doi.org/10.20546/ijcmas.2019.812.293
37. Liu J, Shu A, Song W, Shi W, Li M, Zhang W, et al. Long-term organic fertilizer substitution increases rice yield by improving soil properties and regulating soil bacteria. Geoderma. 2021;404:115287. https://doi.org/10.1016/j.geoderma.2021.115287

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.