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Productivity and Sustainability Assessment of Basmati Rice under Different Crop Establishment Methods and Silicon Fertilization

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Abstract

Purpose

Rice (*Oryza sativa* L.) cultivation in India is increasingly constrained by labour shortages, water scarcity, and declining nutrient-use efficiency. The present study aimed to evaluate the effects of crop establishment methods, silicon fertilization levels, and silicon-solubilizing microbes on yield, nutrient uptake, and sustainability in basmati rice under such resource-limited conditions.

Methods

A two-year field experiment (2023–2024) was conducted using a split–split plot design. The treatments included two crop establishment methods (transplanted and direct-seeded rice), four silicon levels (0, 30, 60, and 90 kg Si ha^{-1}), and two silicon-solubilizing microbes (*Bacillus mucilaginosus* and *Pseudomonas fluorescens*). Data on grain and straw yield, nutrient uptake (N, P, K, and Si), and sustainability index were recorded and analyzed statistically.

Results

Transplanted rice significantly outperformed direct-seeded rice in terms of yield, nutrient uptake, and sustainability index. Application of 90 kg Si ha^{-1} recorded the highest grain yield (3225 kg ha^{-1}) and straw yield (4932 kg ha^{-1}), along with maximum uptake of nitrogen, phosphorus, potassium, and silicon. The sustainability index was also highest under this treatment combination, indicating improved system performance and resource-use efficiency. Silicon-solubilizing microbes did not show a significant effect; however, *Bacillus mucilaginosus* resulted in numerically higher values than *Pseudomonas fluorescens*.

Conclusion

The integration of transplanted rice with 90 kg Si ha^{-1} significantly enhances yield, nutrient uptake, and sustainability index, thereby improving overall system productivity and resource-use efficiency. This combination can be considered a sustainable and efficient strategy for basmati rice cultivation under prevailing constraints of labour and water scarcity.

1. Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half the world's population, contributing approximately 20% of global caloric intake and 31% in India alone [1]. It is cultivated over 162 million hectares globally, with India accounting for nearly 45 million hectares. While the Green Revolution significantly enhanced rice productivity, recent years have witnessed stagnating yields and a decline in total factor productivity due to unsustainable practices and environmental degradation. Among the key challenges confronting rice cultivation today are labor shortages, water scarcity, and inefficient nutrient management.

Traditional rice cultivation through puddled transplanting is labor-intensive and water extensive, making it increasingly unsustainable. Direct-seeded rice (DSR) has emerged as a promising alternative, offering reductions in water and labour requirements by 30–40%, improved soil health, and enhanced resource-use efficiency [2]. Optimal nutrient management, particularly of macronutrients like nitrogen (N), phosphorus (P), and potassium (K), remains critical to maintain productivity. However, conventional fertilizer use has led to imbalanced nutrition, nutrient losses, and environmental problems. Among underutilized nutrients, silicon (Si) has shown substantial potential to improve crop performance by enhancing structural strength, stress tolerance, and nutrient uptake in rice [3, 5]. Beneficial soil microorganisms are gaining recognition for their role in nutrient solubilization and improving nutrient-use efficiency [6]. Microbes such as *Bacillus mucilaginosus* and *Pseudomonas fluorescens* are known to solubilize silicon and other nutrients, complementing chemical inputs [7, 30].

Although individual benefits of silicon fertilization and microbes are known, their combined effects under different establishment methods remain unclear. Therefore, this study was conducted to evaluate their effects on yield, nutrient uptake, and sustainability in basmati rice.

2. Materials and Methods

2.1. Experimental location

A field experiment was conducted in the alluvial zone of Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu district of Jammu & Kashmir, India for two years (2023 and 2024) in the summer season. Experimental field was situated at 32.6529° N latitude, 74.8071° E longitude, and receives mean annual rainfall of 1195 mm with mean annual minimum and maximum temperatures of 24 and 35^{o}C, respectively. The experimental soil belongs to the alluvial soil group, classified as a Typic Haplustept (USDA Soil Taxonomy). It is sandy clay loam in texture and slightly alkaline in reaction (pH 7.49) with low electrical conductivity (0.19 dS m^{-1}) and moderate fertility status (Table 1).

Table 1
Physicochemical properties of experimental soil.

Property	Value
pH (1:2.5 soil/water suspension)	7.49
EC (dS/m)	0.19
Organic Carbon (g kg^{-1})	4.39
Available N (kg ha^{-1})	241.50
Available P (kg ha^{-1})	15.22
Available K (kg ha^{-1})	158.80
Available Si (kg ha^{-1})	253.00
Textural class	
Sand (%)	62.32
Silt (%)	11.64
Clay (%)	26.04
Texture	Sandy clay loam

2.2. Experimental details

Experiment was conducted in split-split plot design replicated thrice. The main plot comprised of two rice establishment methods (transplanted rice and direct-seeded rice). Two seedlings per hill were transplanted in case of transplanting method however, 40 kg ha^{-1}seeds were line-sown for direct-seeded rice. The sub-plot involved four silicon fertilization levels: 0, 30, 60, and 90 kg ha^{-1}, applied as calcium silicate (95% Si) by broadcasting as a basal dose. The sub-sub plot included two silicon-solubilizing microbes, *Bacillus mucilaginosus* and *Pseudomonas fluorescens*, applied through seed or seedling treatment. The main plot measured 34.5 m × 5.0 m (172.5 m²), while both sub- and sub-sub plots had a gross size of 5.0 m × 3.0 m (15 m²) and a net size of 4.2 m × 2.0 m (8.4 m²). Fine rice cultivar Basmati 370 (*Oryza sativa* L.) was used as test crop. Line sowing for direct seeded rice and transplanting was done at a spacing of 20 × 10 cm. The nursery for transplanted rice was sown on 04-06-23 and 04-06-24, and transplanting was carried out on 02-07-23 and 02-07-24 during both years (2023 and 2024). Direct-seeded rice was sown simultaneously at the time of nursery preparation. Harvesting was completed on 07-11-23 and 12-11-24 for each year when the grains reached physiological maturity. A basal fertilizer dose of 30:20:10 kg N:P_2O_5:K_2O ha^{-1} was applied using urea, di-ammonium phosphate, and muriate of potash. One-third of nitrogen and full doses of phosphorus and potassium were applied at planting, with the remaining nitrogen applied in two equal splits at 20 DAT/DAS (tillering) and 45 DAT/DAS (panicle initiation). All crops were managed using recommended package of practices, including chemical weed control and scheduled irrigation.

2.3. Source and composition of Calcium Silicate

Calcium silicate, commercially manufactured by Amgeen Pvt. Ltd., which contains SiO_2 :95%, Calcium (CaO): 2% pH: 9.5–10.5, water absorption: 380% – 400%, bulk density: 0.09–1.12 g cc^{-1} and specific gravity: 2.1, on dry weight basis. Soil application of silicon as calcium silicate was done as basal dose.

2.4. Yield-attributing characteristics and yield

Yield-attributing traits were recorded from one-meter square area randomly selected. Panicle number was counted manually; panicle length and grains per panicle were averaged from ten randomly selected panicles. 1000-grain weight was measured using an electronic balance. Grain and straw yields were recorded from a 4.2 × 2.0 m (8.4 m²) net plot, with grain sun-dried to ~ 14% moisture and weighed. Straw yield was measured from dried aboveground biomass (excluding grain), both expressed in kg/ha (Tables 2 and 3).

Table 2
Effect of crop establishment methods (transplanted rice and direct-seeded rice) and silicon fertilization levels (0, 30, 60, and 90 kg/ha) on yield-attributing traits of basmati rice (cultivar Basmati 370) over two summer seasons (2023 and 2024).

S. No.	Treatments	No. of Panicles m^{-2}		Panicle length(cm)		Grains/Panicle		1000-grain weight (g m^{-2})	
		2023	2024	2023	2024	2023	2024	2023	2024
Main plot: (Crop establishment)									
A_1	Direct Seeded Rice	212.38	214.85	24.02	24.36	67.08	68.20	20.13	20.25
A_2	Transplanted Rice	226.21	229.65	24.74	25.11	72.18	73.50	20.72	20.85
	SEm (±)	04.07	04.12	00.24	00.25	01.40	01.42	00.18	00.19
	CD (5%)	12.21	12.35	NS	NS	04.20	04.25	NS	NS
Sub-plot: (Silicon fertilization)									
S_0	Control	208.45	212.20	23.84	24.10	67.14	68.07	20.03	20.14
S_1	30 kg/ha	213.99	217.50	24.23	24.60	68.66	69.87	20.50	20.59
S_2	60 kg/ha	224.52	226.80	24.72	25.10	70.74	72.07	20.51	20.64
S_3	90 kg/ha	230.21	232.50	24.74	25.15	71.99	73.37	20.69	20.84
	SEm (±)	2.07	02.10	00.11	00.12	00.68	00.70	00.16	00.17
	CD (5%)	6.22	06.30	NS	NS	02.05	02.10	NS	NS
Sub-sub-plot: (Silicon solubilizing microbes)									
M_1	*Bacillus mucilaginosus* (10g/kg seeds or seedlings)	219.98	222.60	24.98	25.02	70.41	71.60	20.47	20.80
M_2	*Pseudomonas Fluorescence* (10g/kg seeds or seedlings)	219.60	221.90	23.77	24.46	68.84	70.10	20.38	20.30
	SEm (±)	01.35	01.40	00.12	00.13	0.18	00.20	0.13	00.14
	CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS

*SEm: Standard error of mean; CD: Critical difference at 5% level; NS: Not Significant

Table 3
Effect of crop establishment methods (transplanted rice and direct-seeded rice) and silicon fertilization levels (0, 30, 60, and 90 kg/ha) on grain and straw yield of basmati rice (cultivar Basmati 370) over two summer seasons (2023 and 2024).

S. No.	Treatments	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})		Sustainablity index
		2023	2024	2023	2024	
Main plot: (Crop establishment)						
A_1	Direct Seeded Rice	2581	2659	4524	4632	0.81
A_2	Transplanted Rice	3020	3061	4768	4851	0.95
	SEm (±)	124.67	126.67	67.33	65.66	-
	CD (5%)	374	380	202	197	-
Sub-plot: (Silicon fertilization)						
S_0	Control	2494	2550	4370	4425	0.78
S_1	30 kg/ha	2658	2717	4519	4590	0.84
S_2	60 kg/ha	2940	3006	4794	4906	0.92
S_3	90 kg/ha	3110	3167	4903	5045	0.98
	SEm (±)	69.66	73.01	68.02	68.33	-
	CD (5%)	209	219	204	205	-
Sub-sub-plot: (Silicon solubilizing microbes)						
M_1	*Bacillus mucilaginosus* (10g/kg seeds or seedlings)	2852	2915	4691	4791	0.90
M_2	*Pseudomonas Fluorescens* (10g/kg seeds or seedlings)	2748	2805	4602	4691	0.86
	SEm (±)	35.01	35.50	29.96	30.00	-
	CD (5%)	NS	NS	NS	NS	-

2.5. Soil and Plant analytical methods

Soil samples were collected from a depth of 0–0.2 meters before the experiment began. The samples were air-dried, grounded, passed through a 2.0-mm sieve and analyzed for pH and electrical conductivity (EC) using a soil-to-water ratio of 1:2.5. The soil texture, including sand, silt, and clay content, was determined using the Bouyoucos hydrometer method. Available nitrogen (N), phosphorus (P), and potassium (K) were determined following the procedures described by Jackson (1958) [33]. The available silicon (Si) content of the soil was estimated using the 0.01 M calcium chloride ($CaCl_2$) extraction method of Haysom and Chapman (1975) [34], which quantifies the plant-available fraction of silicon in soil solution. Although Si is not routinely analyzed in standard soil fertility tests, this method is widely accepted for evaluating available Si for Si-accumulating crops such as rice

After the harvest, grain and straw yields were recorded. Nitrogen concentrations in plant samples were determined using the Kjeldahl method as outlined by Jackson (1958)[33]. For the analysis of phosphorus and potassium, plant samples were digested with a triacid mixture of nitric acid, perchloric acid, and sulfuric acid in a 9:3:1 ratio. (HNO_3/$HClO_4$/H_2SO_4 9:3:1).

2.6. Silicon (Si) analysis in plant samples

Silicon in plant samples was estimated using the method described by Ma et al. (2020) [3]. Plant samples were taken at harvest and whole plant with grain is dried in an oven at 70°C for 2–3 hours, and 0.1g of the powdered sample was digested in a mixture of 7 ml of 62% nitric acid (HNO_3) and 2 ml of hydrogen peroxide (H_2O_2, 30%). The mixture was left for 10–15 minutes for pre-digestion. After digestion, the samples were diluted to 50 ml with 4% boric acid. The silicon concentration in the digested solution was determined by transferring 0.1 ml of the digested aliquot to a plastic centrifuge tube, adding 3.75 ml of 0.2N hydrochloric acid (HCl), 0.5 ml of 10% ammonium molybdate, 0.5 ml of 20% tartaric acid, and 0.5 ml of a reducing agent (ANSA), and then making up the volume to 12.5 ml with distilled water. After 1 hour, the absorbance was measured at 600 nm using a UV-visible spectrophotometer.

2.6 Sustainability Analysis

The sustainability of different treatments was assessed using grain yield data from two consecutive years (2023 and 2024). The Sustainability Index (SI) was calculated to evaluate yield stability and consistency using the formula:

$$SI = \frac{\overset{'}{Y} - SD}{Y_{max}}$$

where $\overset{'}{Y}$ is the mean grain yield (kg ha⁻¹), SD is the standard deviation over years, and Y_{max} is the maximum yield observed in the experiment.

The mean and standard deviation were computed from two-year yield data, and the maximum yield of 3167 kg ha⁻¹ (recorded under 90 kg Si ha⁻¹ in 2024) was used as the reference. Higher SI values (closer to 1.0) indicate greater sustainability and yield stability, whereas lower values reflect higher variability and reduced sustainability.

2.8. Statistical analysis

The biomass yield (straw and grain), yield-attributing characteristics, and the uptake of N, P, K, and Si data were subjected to ANOVA using a split-split plot design to assess the main and interaction effects of crop establishment methods, silicon fertilization levels, and silicon solubilizing microbes. Significant differences were separated using the LSD test at a 0.05 probability level with SPSS software (version 17.0, SPSS Inc., Chicago, USA). Additionally, Pearson's Correlation Analysis was performed to assess relationships among key yield attributes such as grain yield, straw yield, number of panicle/m^2, panicle length, grains per panicle, and 1000-grain weight. The correlation matrix was computed to determine the strength and direction of relationships between these variables. Correlation coefficients (r-values) were tested for significance at the 1% and 5% probability levels, and the results were represented in a heatmap for easier interpretation.

3. Results

3.1. Yield attributes and yield of rice

Statistical analysis of data revealed that crop establishment methods and silicon fertilization significantly influenced the yield attributes and grain yield of rice during both crop growing seasons of 2023 and 2024 (Table 2 and Table 3). Among the establishment methods, transplanted rice (TPR) produced a significantly highest number of panicles m⁻² compared with direct-seeded rice (DSR). TPR recorded 226.21 and 229.65 panicles m⁻² during 2023 and 2024, respectively, whereas DSR produced 212.38 and 214.85 panicles m⁻² in the corresponding years. A similar trend was observed for grains panicle⁻¹, where TPR resulted in significantly highest values (72.18 in 2023 and 73.50 in 2024) in comparison to DSR (67.08 and 68.20 in 2023 and 2024, respectively), representing an overall increase of about 7.6%. In contrast, the effect of crop establishment method on panicle length and 1000-grain weight was not statistically significant. However, TPR recorded numerically higher values than DSR across both years. Further, among silicon treatments, application of 90 kg Si ha⁻¹ resulted in a significantly greater number of panicles m⁻² (230.21 in 2023 and 232.50 in 2024). A comparable trend was observed for grains panicle⁻¹, where the highest values (71.99 and 73.37 in 2023 and 2024, respectively) were recorded with 90 kg Si ha⁻¹; however, these remained statistically at par with 60 kg Si ha⁻¹.Although, panicle length and 1000-grain weight did not differ significantly due to silicon levels, highest silicon dose of 90 kg Si ha⁻¹ produced numerically superior results recording panicle length of 24.74 cm in 2023 and 24.90 cm in 2024, along with 1000-grain weight of 20.69 g and 20.84 g, respectively as compared to other treatments.

Transplanted rice (TPR) recorded significantly highest grain yield than direct-seeded rice (DSR) during both years of study. Rice established through transplanting recorded grain yield of 3020 and 3061 kg ha⁻¹ in 2023 and 2024, respectively whereas direct seeding resulted in 2581 and 2659 kg ha⁻¹. A similar trend was observed for straw yield, which was also significantly highest under TPR (4768 and 4851 kg ha⁻¹ in 2023 and 2024, respectively) compared with DSR (4524 and 4632 kg ha⁻¹, respectively). Among silicon levels, application of 90 kg ha^{-1} resulted in higher grain yield of 3110 kg ha^{-1} (2023) and 3167 kg ha^{-1} (2024), representing an increase of 23.4% over the control. Straw yield followed a similar trend, with the highest values of 4903 kg ha^{-1} in 2023 and 5045 kg ha^{-1} in 2024 under 90 kg Si ha^{-1}, showing a 14.2% improvement compared to the control.

Although the use of silicon solubilizing microbes did not lead to statistically significant differences, *Bacillus mucilaginosus* consistently recorded numerically higher values. It achieved grain yields of 2852 kg ha^{-1} (2023) and 2915 kg ha^{-1} (2024), and straw yields of 4691 kg ha^{-1} and 4791 kg/ha, respectively, compared to *Pseudomonas fluorescens*, which recorded slightly lower values during both years of experiment.

3.2 Sustainability Index

Sustainability Index (SI) indicated that crop establishment methods and silicon fertilization markedly influenced the sustainability of rice production based on grain yield data over two consecutive years (2023 and 2024) (Table 3). Among the establishment methods, transplanted rice (TPR) exhibited a higher sustainability index (0.95) compared to direct-seeded rice (DSR) (0.81), indicating greater yield stability and consistency under transplanted conditions. Among silicon fertilization levels, a progressive increase in sustainability index was observed with increasing silicon application. The highest SI value (0.98) was recorded with 90 kg Si ha⁻¹, followed by 60 kg Si ha⁻¹ (0.92) and 30 kg Si ha⁻¹ (0.84), whereas the control treatment registered the lowest SI (0.78). The higher SI under increased silicon levels reflects not only enhanced productivity but also reduced inter-annual variability in grain yield. In the case of silicon solubilizing microbes, although differences were not statistically significant, *Bacillus mucilaginosus* recorded a relatively higher sustainability index (0.90) compared to *Pseudomonas fluorescens* (0.86). Overall, the results suggest that transplanted rice combined with higher silicon fertilization (90 kg ha⁻¹) contributes to improved sustainability of rice production by ensuring higher and more stable grain yield across years.

3.2. Nutrient uptake by rice grain and straw

Crop establishment practices along with silicon fertilization resulted in a significant influence on the uptake of major nutrients (N, P, K) and silicon during both experimental years (Table 4; Fig. 2). Transplanted rice (TPR) consistently exhibited significantly highest nutrient accumulation than direct-seeded rice (DSR) where total nitrogen uptake under TPR was 63.88 kg ha⁻¹ in 2023 and 66.13 kg ha⁻¹ in 2024, representing an increase of about 20.1% over DSR, which recorded 52.69 and 54.16 kg ha⁻¹ in the respective years. A similar response was observed for phosphorus uptake, where TPR registered significantly highest phosphorous uptake of 23.01 and 23.97 kg ha⁻¹ during 2023 and 2024, respectively compared with 20.12 and 22.24 kg ha⁻¹ under DSR, reflecting a 15.1% advantage. Potassium uptake also followed a similar pattern, with TPR resulting in uptake of 108.22 and 110.13 kg ha⁻¹ in the two years against 98.89 and 100.95 kg ha⁻¹ under DSR. In terms of silicon accumulation, TPR resulted in significantly highest uptake of 314.45 kg ha⁻¹ in 2023 and 335.15 kg ha⁻¹ in 2024, whereas the corresponding values under DSR were 302.63 and 309.84 kg ha⁻¹. Further, application of silicon at 90 kg ha^{-1} resulted in significantly highest

nutrient uptake across both years (Fig. 1) where, total nitrogen uptake under 90 kg Si ha^{-1} was 70.65 kg ha^{-1} in 2023 and 72.93 kg/ha in 2024, registering 60.3% increase over the control. Similarly phosphorus uptake was recorded to be significantly highest under 90 kg Si ha^{-1} (23.64 kg ha^{-1} and 25.30 kg ha^{-1} during 2023 and 2024, respectively), which was 21.8% higher than the control. Potassium uptake (107.16 kg ha^{-1} and 108.80 kg ha^{-1}) was also recorded to be significantly highest under 90 kg Si ha^{-1}, compared to as compared to other treatments. Additionally, highest total silicon uptake was also recorded at 90 kg Si ha^{-1} with 313.91 kg ha^{-1} (2023) and 327.42 kg ha^{-1} (2024), showing an increase of over 22% in comparison to the control.

Table 4

Effect of crop establishment methods (transplanted rice and direct-seeded rice) and silicon fertilization levels (0, 30, 60, and 90 kg/ha) on NPK and Silicon u

S. No.	Treatments	Nitrogen (kg ha^{-1})						Phosphorous (kg ha^{-1})						Potassium (kg ha		
		Grain		Straw		Total		Grain		Straw		Total		Grain		Stra
		2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	202
Main plot: (Crop establishment)																
A_1	Direct Seeded Rice	33.01	33.67	19.68	20.49	52.69	54.16	8.26	9.25	11.86	12.99	20.12	22.24	12.71	13.04	86.1
A_2	Transplanted Rice	38.15	39.50	25.73	26.63	63.88	66.13	9.47	9.96	13.53	14.01	23.01	23.97	15.29	15.59	92.9
	SEm (±)	1.35	1.36	1.42	1.45	3.14	03.16	0.35	0.23	0.37	0.33	0.68	0.36	0.81	0.83	0.96
	CD (p = 5%)	4.05	4.10	4.28	4.35	9.41	9.50	1.05	0.69	1.11	1.01	2.05	1.10	2.45	2.50	2.88
Sub-plot: (Silicon fertilization)																
S_0	Control	28.90	29.50	16.20	17.03	45.10	46.53	8.14	8.74	11.15	12.15	19.29	20.89	13.03	13.26	87.2
S_1	30 kg/ha	32.60	33.86	19.62	20.25	52.22	54.11	8.56	9.31	11.93	12.59	20.49	21.90	13.28	13.69	88.3
S_2	60 kg/ha	39.51	40.01	25.65	27.01	65.16	67.02	9.28	10.03	13.55	14.30	22.83	24.33	14.50	14.80	90.7
S_3	90 kg/ha	41.30	42.98	29.35	29.95	70.65	72.93	9.49	10.34	14.15	14.96	23.64	25.30	15.20	15.50	91.9
	SEm (±)	1.43	1.46	1.41	1.43	2.75	2.80	0.19	0.20	0.32	0.33	0.41	0.36	0.34	0.35	0.77
	CD (p = 5%)	4.30	4.40	4.24	4.30	8.26	8.40	0.59	0.60	0.98	0.99	1.22	1.10	1.02	1.05	2.31
Sub-sub-plot: (Silicon solubilizing microbes)																
M_1	*Bacillus mucilaginosus* (10g/kg seeds or seedlings)	35.67	36.69	22.77	23.66	58.44	60.35	9.04	9.76	12.79	13.60	21.83	23.36	14.25	14.51	89.8
M_2	*Pseudomonas fluorescens* (10g/kg seeds or seedlings)	35.48	36.49	22.64	23.46	58.12	59.95	8.69	9.46	12.60	13.40	21.29	22.86	13.75	14.11	89.2
	SEm (±)	0.06	0.07	0.04	0.05	0.33	0.35	0.09	0.10	0.06	0.07	0.21	0.22	0.17	0.18	0.18
	CD (p = 5%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
.																

Application of silicon solubilizing microbes failed to produce statistically significant differences. However, treatments inoculated with *Bacillus mucilaginosus* consistently recorded numerically higher values for nutrient uptake in comparison to *Pseudomonas fluorescens*. Plots inoculated with *Bacillus mucilaginosus* recorded higher total nitrogen uptake (58.44 kg ha^{-1} and 60.35 kg ha^{-1}), phosphorus uptake (21.83 kg/ha and 23.36 kg ha^{-1}), potassium uptake (104.08 kg ha^{-1} and 106.09 kg ha^{-1}) and silicon uptake (311.10 kg ha^{-1} and 325.48 kg ha^{-1}) in 2023 and 2024 respectively.

The correlation heatmap of pooled yield attributes and yield data reveals strong positive associations among the variables studied. Grain yield (kg/ha) exhibited a perfect correlation (r = 1.00) with panicles per m^2, indicating that the number of panicles per unit area is a critical determinant of grain yield. Similarly, panicle length (r = 0.98) and grains per panicle (r = 0.98) also showed a strong positive correlation with grain yield, suggesting their direct role in enhancing productivity. The thousand grain weight was moderately correlated with grain yield (r = 0.96), emphasizing the importance of grain size and weight in overall yield performance. Additionally, straw yield was positively associated with grain yield (r = 0.95), implying a synchronous increase in vegetative biomass with reproductive output. These correlations highlight the synergistic influence of yield components on final grain productivity and underline the importance of optimizing all contributing attributes to maximize rice yield (Fig. 3).

4. Discussion

The significant improvement in yield attributes and yield of rice observed under transplanted rice (TPR) compared to direct-seeded rice (DSR) can be attributed to better crop establishment and enhanced early crop vigor. Transplanting ensures a uniform plant stand and minimizes intra-specific competition during the critical growth stages, thereby promoting better tillering and biomass accumulation. These advantages were reflected in higher number of panicles, grains per panicle, and ultimately higher grain and straw yield under TPR across both years. Similar findings have been reported earlier, where transplanted rice exhibited superior physiological performance due to enhanced tillering capacity and stronger root anchorage, leading to improved sink strength and grain filling efficiency [4, 19].

Silicon fertilization significantly enhanced yield attributes and overall productivity, with the highest response observed at 90 kg ha^{-1}. The increase in panicle number and grains per panicle, along with higher grain yield, indicates that silicon improved both structural stability and physiological efficiency of the crop. Silicon deposition in plant tissues strengthens cell walls and culm rigidity, thereby reducing lodging and maintaining erect leaf orientation, which enhances light interception and photosynthetic efficiency [12, 17]. Improved canopy architecture and prolonged leaf activity likely contributed to better assimilate translocation during reproductive stages, resulting in enhanced grain filling. These results are in agreement with previous studies reporting that silicon application improves yield components and stress tolerance in rice [10, 21, 28].

Although silicon-solubilizing microbial inoculation did not show statistically significant effects, *Bacillus mucilaginosus* consistently recorded numerically higher values for yield and yield attributes compared to *Pseudomonas fluorescens*. This may be attributed to its ability to solubilize silicate minerals and increase the availability of plant-accessible silicon in the rhizosphere. Similar observations have been reported, where beneficial microorganisms enhanced crop productivity through improved nutrient solubilization and uptake [30, 8].

The higher sustainability index observed under transplanted rice compared to direct-seeded rice indicates better yield stability and consistency across years. This may be due to more efficient resource utilization and reduced environmental variability under transplanting conditions [2]. Furthermore, the progressive increase in sustainability index with increasing silicon levels highlights the role of silicon in improving stress tolerance and stabilizing yield performance. Silicon enhances plant resilience against abiotic and biotic stresses, thereby reducing inter-annual yield variability [17, 21]. Although microbial treatments were non-significant, relatively higher sustainability under *Bacillus mucilaginosus* suggests its supportive role in improving nutrient availability and system stability [7].

The significantly higher uptake of nitrogen, phosphorus, potassium, and silicon under transplanted rice and higher silicon levels reflects improved nutrient availability and plant absorption efficiency. Transplanted rice provides favourable soil moisture conditions and promotes better root development, which enhances nutrient uptake compared to direct-seeded systems [31, 19]. Additionally, silicon application, particularly at 90 kg ha^{-1}, increased nutrient uptake across both years, highlighting its integrative role in plant nutrition. Silicon improves nutrient-use efficiency by enhancing root growth, reducing nutrient losses, and improving internal nutrient translocation [21, 3]. Enhanced nitrogen uptake may be associated with reduced leaching losses and improved retention, while increased phosphorus uptake can be attributed to improved root architecture and rhizospheric mobilization. Similarly, higher potassium uptake may result from improved water relations and ion transport mechanisms [17, 28]. The increased silicon uptake reflects greater availability and accumulation in plant tissues, which further strengthens plant structure and enhances physiological efficiency. Although microbial effects were non-significant, *Bacillus mucilaginosus* consistently improved nutrient uptake, likely due to its role in solubilizing silicate minerals and enhancing nutrient availability [30, 16].

5. Conclusions

The findings of the present investigation clearly indicate that establishment of rice through transplanting method along with application of silicon application at 90 kg ha^{-1} significantly enhances both productivity and nutrient accumulation in rice. This treatment combination produced the maximum grain yield (3225 kg ha^{-1}) and straw yield (4932 kg ha^{-1}), along with the higher uptake of nitrogen (70.70 kg ha^{-1}), phosphorus (23.47 kg ha^{-1}), potassium (96.02 kg ha^{-1}), and silicon (329.70 kg ha^{-1}). The synergistic benefits of improved crop establishment and adequate silicon supply strengthen plant structural integrity, increase tolerance to environmental stresses and improve nutrient-use efficiency, thereby providing a promising and sustainable management option for irrigated subtropical rice production systems. In addition, inoculation with *Bacillus mucilaginosus* slightly improved rice productivity. Although these increases were not statistically significant, they nevertheless indicate its potential as a cost-effective and environmentally friendly biological input. However, validation through multi-location and long-term field studies is required before recommending its widespread adoption across diverse rice-growing environments.

Abbreviations

ANOVA, analysis of variance; CaO, calcium oxide; CD, critical difference; DAP, di-ammonium phosphate; DAT/DAS, days after transplanting/sowing; DSR, direct seeded rice; EC, electrical conductivity; FAOSTAT, Food and Agriculture Organization Corporate Statistical Database; HCl, hydrochloric acid; $HClO_4$, perchloric acid; HNO_3, nitric acid; H_2O_2, hydrogen peroxide; H_2SO_4, sulfuric acid; K, potassium; K_2O, potassium oxide; LSD, least significant difference; Mg, megagram; N, nitrogen; NS, not significant; P, phosphorus; P_2O_5, diphosphorus pentoxide; SEm, standard error of mean; Si, silicon; SiO_2, silicon dioxide; SPSS, Statistical Package for the Social Sciences; TPR, transplanted rice; UV, ultraviolet; UV-visible spectrophotometer, ultraviolet-visible spectrophotometer.

Declarations

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Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interest

The authors declare financial or non-financial competing interests

Authors contribution:

Joy Samuel MeCarty: Conducted the field experiment and performed the research work,

Neetu Sharma: Conceptualized the study, developed the research idea, and supervised the overall investigation. Faraaz Farooq: Prepared the manuscript and contributed to data interpretation.

Swati Mehta: Table formatting and supervision

Rakesh Kumar: Graphical preparation and overall editing of manuscript

C. Lalrammawii: Involved in data collection and field observations.

Hri-tik Srivastava: Contributed to data analysis

Conflicts of Interest

The authors declare no conflict of interest.

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Figures

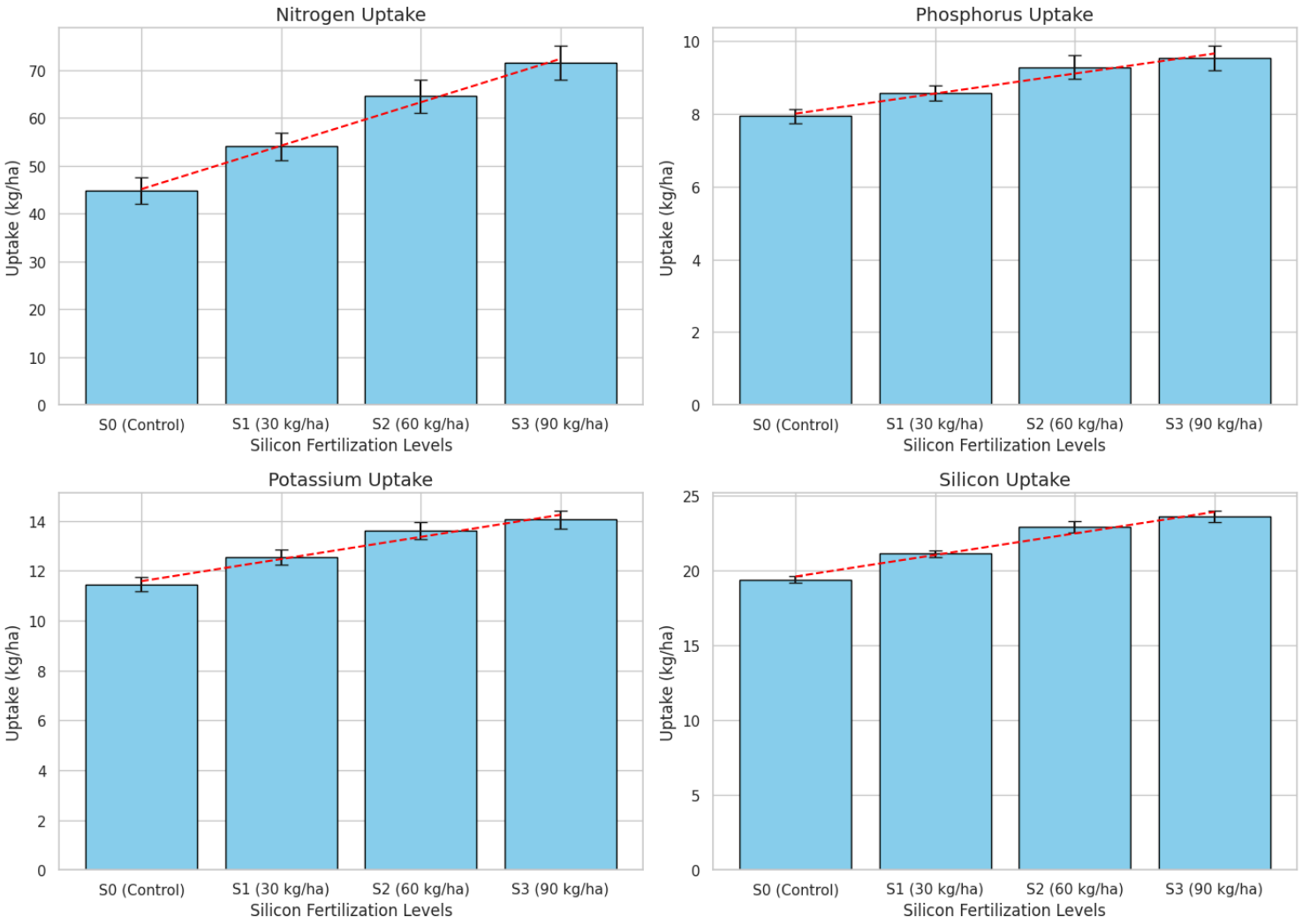


Figure 1

Effect of different silicon fertilization on nutrient and silicon uptake by rice (pooled data).

***Error bar= SEm**(±)

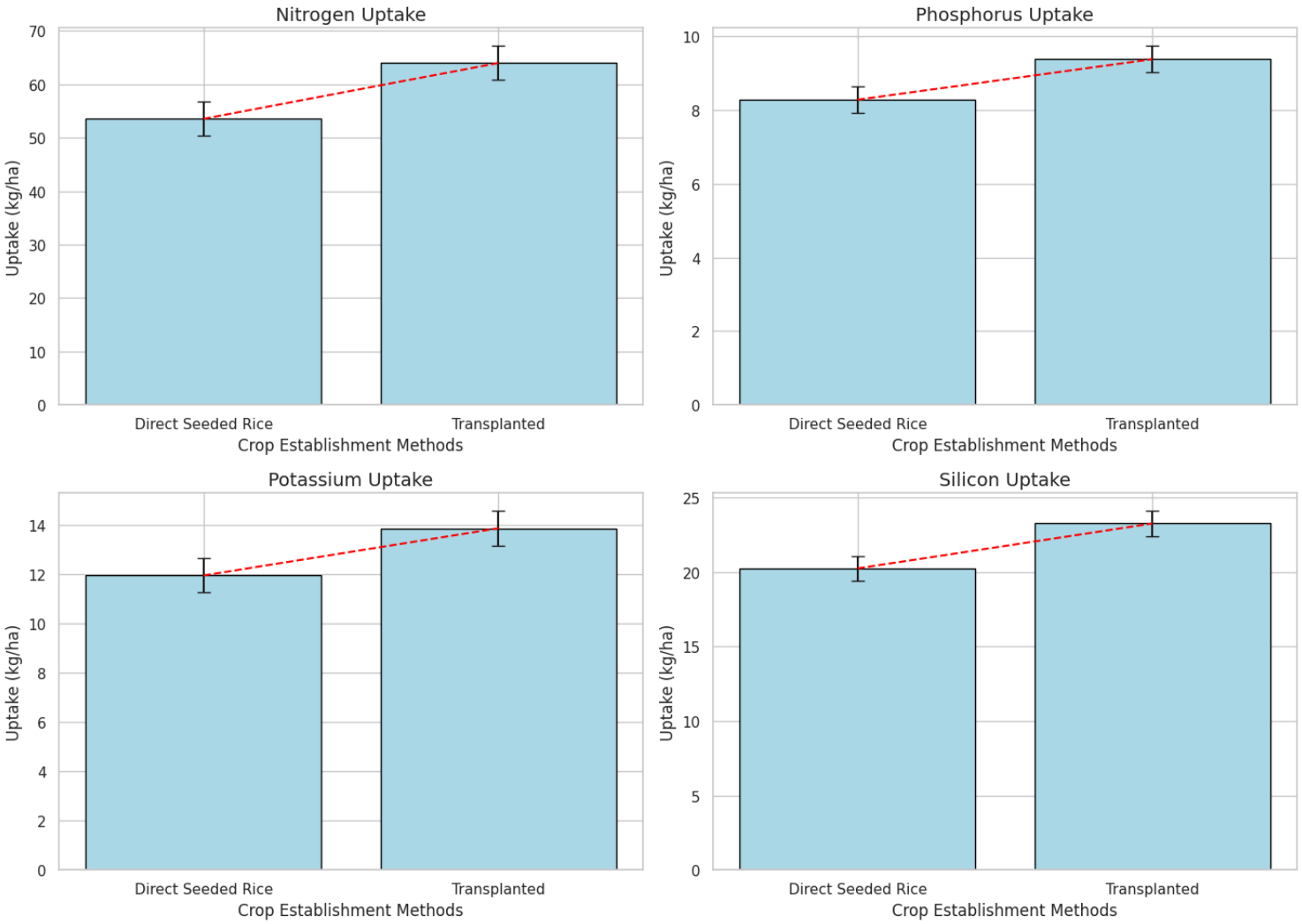


Figure 2

Effect of silicon solubilizing microbes on nutrient and silicon uptake by rice (pooled data).

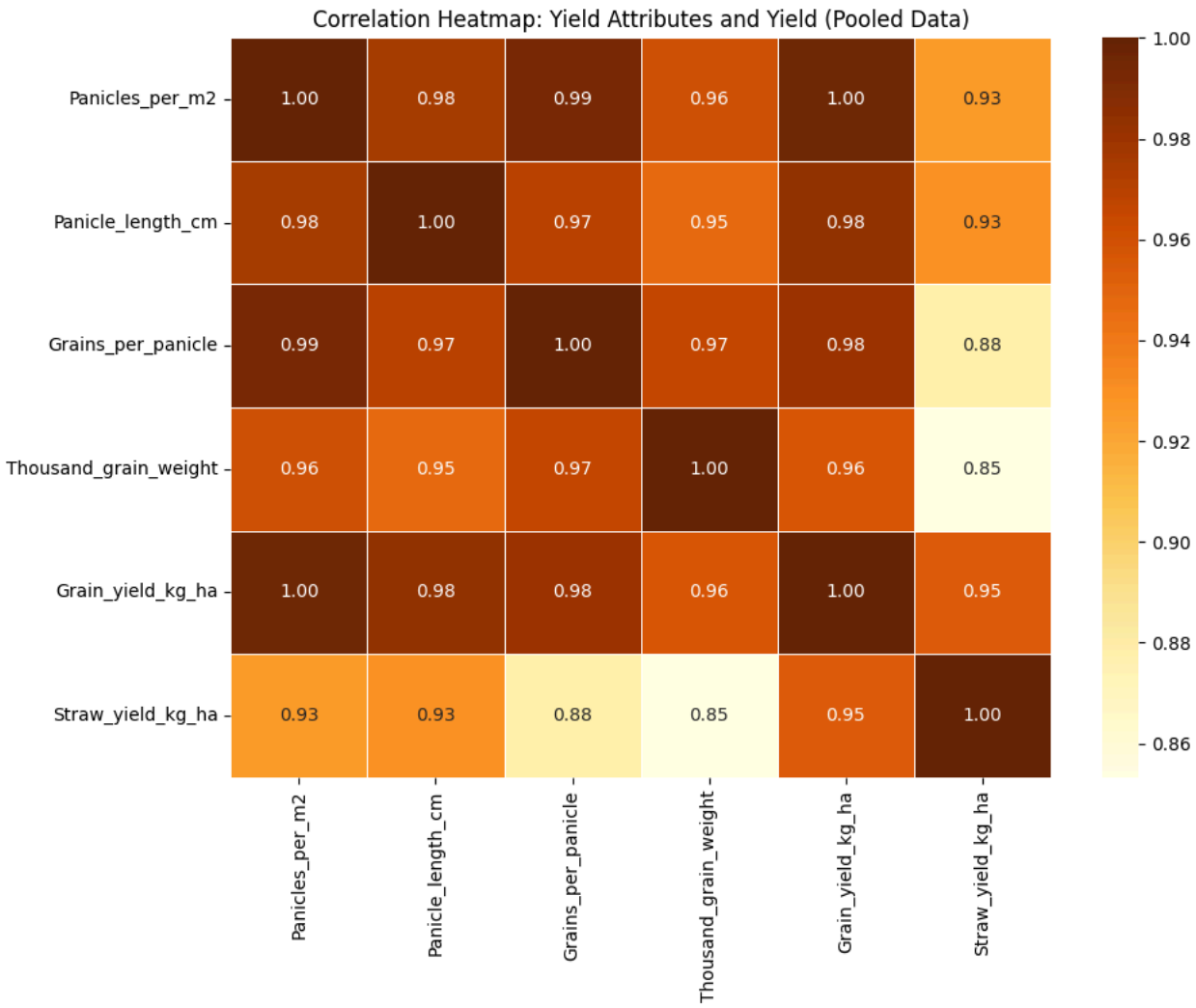


Figure 3

Correlation matrix heatmap showing relationships between yield attributes (e.g., number of panicles/m², grains per panicle, panicle length, 1000-grain weight) and yield (grain and straw) in fine rice (Basmati 370) over pooled data from 2023–2024.