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RESEARCH ARTICLE

Impact of crop establishment methods, silicon fertilization and silicon solubilizing microbes on growth and economic of basmati rice (*Oryza sativa* L.)

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Abstract

A field experiment was conducted to evaluate the effect of crop establishment methods, silicon (Si) fertilization and silicon solubilizing microbes on growth attributes and economics of basmati rice during the *Kharif* (summer) season of 2023 and 2024 at Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, India. The experiment was laid out in a split-split plot design with three replications. Under main plot, crop establishment methods (transplanted rice and direct seeded rice) were used, whereas under sub-plot different levels of silicon fertilization (control, 30 kg/ha, 60 kg/ha, 90 kg/ha) and under sub-sub plot, silicon solubilizing microbes was used (*Bacillus mucillaginosus* and *Pseudomonas fluorescens*). The experimental results revealed that among the crop establishment methods, transplanted rice recorded significantly higher values in terms of plant height, number of tillers/m^2, leaf area index, dry matter accumulation and crop growth rate (CGR). In addition, transplanted rice resulted in the highest gross returns, net returns and B:C ratio, indicating its economic superiority over other methods. Similarly, among different silicon fertilization levels, the application of 90 kg Si/ha recorded significantly higher values for plant height, number of tillers/m^2, leaf area index, dry matter accumulation, CGR, gross returns, net returns and B:C ratio. However, it was found to be statistically at par with the application of 60 kg Si/ha, suggesting that both levels were effective in improving crop performance and profitability. These findings highlight the importance of adopting suitable crop establishment methods and optimal silicon fertilization for improving the growth, yield attributes and economic viability of basmati rice cultivation.

Keywords: calcium silicate; economics; growth attributes; silicon fertilization

Introduction

Rice is a staple food for over 50 % of the world's population, providing 20 % of the total calories consumed globally and 31 % of the calories required by the Indian population. Worldwide, rice is grown on approximately 162.06 million hectares, yielding about 700 million tonnes (1). In India, it is cultivated on around 45 million hectares, producing 137.83 million tonnes (1). The introduction of high-yielding varieties and improved crop management practices during the green revolution significantly boosted productivity. However, recent evidence suggests that productivity has plateaued and total factor productivity is declining due to ongoing environmental degradation. To address the yield constraints in rice cultivation, there is an urgent need to adopt improved crop management practices. Among these practices, the method of crop establishment is crucial for achieving optimal plant population and ensuring agro-ecological sustainability. Inadequate crop establishment can significantly reduce yields. In India, rice is traditionally established by transplanting 25- to 30-day-old seedlings into a puddled paddy field, a process that is cumbersome, costly and labor-intensive. Moreover, continuous flooding for rice cultivation places a significant strain on already limited freshwater resources and often leads to lower water productivity (2-5). Therefore, it is essential to develop alternative rice production systems that optimize the use of energy, labor and water. Direct seeding is one such option that could offer a more sustainable approach to rice cultivation. Direct seeded rice (DSR) is a method where rice seeds are sown directly into the field without the need for a nursery or transplanting. This technique, which includes method like "*Kera*" (furrow sowing) which offers significant benefits such as reduced water usage, lower labor costs and better soil health. DSR can save up to 30-40 % water and labour, making it a cost-effective and environmentally friendly alternative to traditional rice cultivation (6-8).

Meeting the increasing food demand while minimizing environmental impact has become a significant challenge for farmers and scientists. To achieve optimal rice productivity, proper plant nutrition through the supply of essential macro and micronutrients is vital. Among the macronutrients, nitrogen (N), phosphorus (P) and potassium (K) are particularly important (9, 10). Nitrogen promotes plant growth, enhances tillering and improves grain quality (11); phosphorus supports root development and flowering; while potassium aids in carbohydrate synthesis and disease resistance. Proper nutrient management ensures these nutrients are available in adequate amounts throughout the crop's growth stages (12). However, despite traditional fertilization practices, declining yields in Indian rice fields have highlighted the need for additional nutrient strategies. Silicon (Si) fertilization has emerged as a promising solution due to its multifunctional role in enhancing rice productivity. Silicon strengthens plant cell walls, improves leaf erectness and boosts resistance to biotic and abiotic stresses such as pest attacks, drought and salinity conditions frequently encountered in Indian rice-growing regions (12). Additionally, silicon facilitates better nutrient uptake, especially of N, P and K, ensuring balanced plant nutrition. Incorporating Si fertilization into conventional nutrient management practices can significantly improve rice yields and sustainability in India's intensive agricultural systems. Si is the second most abundant nutrient in the soil, is considered an "agronomically essential element" and one of the most beneficial nutrients for rice cultivation, as rice requires substantial amounts of silica for its growth. The Si content in soils can vary widely, ranging from less than 1 % to 45 % by dry weight (13) and plants absorb Si in the form of silicic acid [$Si(OH)_4$]. Demonstrating the essentiality of Si as a nutrient for higher plants is challenging due to its ubiquitous presence in the biosphere. It is estimated that rice plants remove nearly 20 kg of silicon from the soil to produce 100 kg of rice (14). The most beneficial effects of Si are attributed to the formation of silica gel, which is deposited on the surfaces of leaves, stems and other organs of rice plants (15). Studies have shown that the uptake of Si in rice and sugarcane can sometimes exceed that of N and K (16). Due to its synergistic effects, Si application has the potential to increase the optimal nitrogen rate, thereby enhancing rice productivity. Rice is considered a Si accumulator plant, actively accumulating Si to tissue concentrations of 5 % or higher. Recently, Si has been regarded as a quasi-essential element for the growth of higher plants. Research suggests that Si enhances disease resistance, contributes to cell wall turgidity and plays a role in mitigating metal toxicities (17).

Conventional farming practices heavily depend on chemical fertilizers, which, though effective, often lead to soil degradation and environmental pollution. In this context, biofertilizers have emerged as a sustainable alternative for improving rice productivity while maintaining soil health (18, 19). Biofertilizers are organic products containing beneficial microorganisms that enhance nutrient availability through natural processes, supporting plant growth and yield (20). Key functions of biofertilizers in rice production include nitrogen fixation, phosphorus mobilization and improved nutrient uptake (21). Nitrogen-fixing biofertilizers such as *Azospirillum* and *Rhizobium* convert atmospheric nitrogen into plant-usable forms, particularly valuable in nitrogen-deficient and acidic soils common in Indian agricultural landscapes (22). Similarly, phosphorus-solubilizing microorganisms like mycorrhizal fungi release phosphorus from insoluble compounds, ensuring better root access to this critical nutrient (23). Additionally, biofertilizers enhance root development, enabling more efficient water and nutrient absorption. Biofertilizers also play a vital role in boosting plant resilience against biotic and abiotic stresses, such as drought, salinity and pest attacks-conditions frequently encountered in India's rice-growing regions. Integrating biofertilizers with chemical fertilizers can optimize nutrient management by reducing chemical input while maintaining or even enhancing rice yields. Additionally, several microbes, such as *Bacillus caldolytyicus*, *Bacillus mucilaginosus var. siliceous*, *Proteus mirabilis*, *Pseudomonas* and *Penicillium*, have been reported to release silica from natural silicates (24). Considering a field experiment was conducted to study the effect of crop establishment methods Si and silicon solubilizing microbes fertilization on nutrient uptake and productivity of fine rice.

Materials and Methods

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 consecutive years (2023 and 2024) in the *Kharif* season. The experimental field is 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 °C, respectively. The soil type is sandy clay loam in texture and slightly alkaline in reaction (Table 1).

Experimental details

The experiment was laid out in split-split plot design and replicated thrice. The experiment was conducted with 16 treatment combinations including two rice establishment methods in main plot, four Si application levels in sub plot and Si solubilizing microbes in sub-sub plot. Main plot treatments in rice crop included direct seeded rice (A1) and transplanted rice (A2). Seed rate of 25 kg/ha was used for transplanted rice and 40 kg/ha was used for direct seeded rice (line sowing). Sub plot treatments in rice crop had four level of Si application (0, 30, 60 and 90 kg/ha) (S0, S1, S2 and S3, respectively) and sub-sub plot included two Si solubilizing microbes, *viz*., *B. mucilaginosus* (M1) and *Pseudomonas fluorescens* (M2). Fine rice cultivar basmati 370 was taken as test crop. Rice crop was sown/transplanted at a spacing of 20 cm × 15 cm in main plot. Rice crop was supplied with 30:20:10 kg $N:P_2O_5:K_2O$ kg/ha respectively. One third quantity of N and entire quantity of P and K was applied at the time of transplanting/sowing. Remaining N was applied in two equal splits – at tillering (20 DAT/DAS) and panicle initiation stage (45 DAT/DAS). The crop was supplied through inorganic sources of nutrients *viz*., urea, di-ammonium phosphate and muriate of potash. Si was applied through calcium silicate which contains 98 % of Si as per the treatment details before transplanting/sowing of rice by broadcasting method as basal dose except in control (no Si treatment). Inoculation of Si solubilizing microbes was done through seed/seedling treatment. Recommended package of practices such as chemical weed management, irrigation was followed for raising rice crop.

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)	4.39
Available N (kg/ha)	241.50
Available P (kg/ha)	15.22
Available K (kg/ha)	158.80
Available Si (kg/ha)	253.00
Textural class	
Sand (%)	62.32
Silt (%)	11.64
Clay (%)	26.04
Texture	Sandy clay loam

Source and composition of calcium silicate

Calcium silicate, commercially manufactured by Amgeen Pvt. Ltd., which contains SiO_2: 98 %, calcium (Ca): 2 % pH: 9.5-10.5, water absorption: 380-400 %, Bulk Density: 0.09-1.12 gm/Cc and Sp. Gravity: 2.1, on dry weight basis.

Observations recorded

The observations for various growth parameters *viz*., plant height (cm), dry matter accumulation (g/plant) were recorded periodic intervals of 30, 60 and 90 DAS at harvest. Five plants were tagged in each plot to measure the plant height and was measured with the help of meter scale from ground base of the plant to the uppermost tip. For dry matter accumulation plants were taken from penultimate row and were cut closely to soil surface from each plot. The samples were sundried and thereafter shifted in the oven to dry at a temperature of 65 ± 5 °C till constant weight was achieved. Leaf area index (LAI) was recorded at an interval of 30, 60 and 90 DAS. The leaves are designated into small, medium and large categories and the number of leaves in each of these categories were counted. Leaf area was determined with the help of length and breadth method and it was calculated by using the formulae given below (Eqn. 1):

Land area per plant = Row distance × plant distance

$$\text{Leaf area index (LAI)} = \frac{\text{Leaf area (cm}^2)}{\text{Land area (cm}^2)} \qquad \text{(Eqn. 1)}$$

Gross return, net return and benefit-cost (B:C) ratio were calculated to assess the economic viability of the treatments. Gross return was computed by multiplying the total grain and straw yield (kg/ha) by their respective market prices (₹/kg). Net return was determined by subtracting the total cost of cultivation (including seed, fertilizers, labor, irrigation and other inputs) from the gross return. The B:C ratio was calculated as the ratio of gross return to the total cost of cultivation.

Statistical analysis

Growth attributes and nutrient use indices were subjected to ANOVA using a split-split plot design to assess the main and interaction effects of crop establishment, Si fertilization levels and Si 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).

Results

Growth attributes

Plant height (cm)

Among the crop establishment methods, transplanted rice (A2) recorded significantly higher plant height at all growth stages compared to direct-seeded rice (A1). At 30 DAS, transplanted rice had a plant height of 35.24 cm, which was 19.0 % higher than direct-seeded rice at 29.60 cm. This trend continued at 60 DAS (79.45 cm vs. 73.24 cm, 8.5 % higher), 90 DAS (122.23 cm vs. 116.85 cm, 4.6 % higher), 120 DAS (144.26 cm vs. 139.37 cm, 3.5 % higher) and at harvest (148.66 cm vs. 141.45 cm, 5.1 % higher).

The application of Si significantly influenced plant height, with higher doses of Si resulting in increased plant height. At 30 DAS, the control (S0) recorded a plant height of 31.66 cm, while 90 kg/ha Si (S3) resulted in a plant height of 32.99 cm (4.2 % higher). This trend was consistent at subsequent stages, with S3 recording the highest plant height at 60 DAS (80.30 cm, 11.3 % higher than control), 90 DAS (124.48 cm, 8.1 % higher than control), 120 DAS (146.87 cm, 7.3 % higher than control) and at harvest (147.78 cm, 4.2 % higher than control). The lowest plant height was observed in the control (S0) across all stages.

The application of Si solubilizing microbes also influenced plant height, though the differences were not statistically significant. *B. mucilaginosus* (M1) resulted in slightly higher plant heights compared to *P. fluorescens* (M2) at all growth stages. For example, at 90 DAS, M1 recorded a plant height of 120.50 cm, which was 1.6 % higher than M2 at 118.58 cm (Fig. 1).

Number of tillers/m^2

Among the crop establishment methods, transplanted rice (A2) recorded a significantly higher number of tillers at all growth stages compared to direct-seeded rice (A1). At 30 DAS, transplanted rice had 87.02 tillers, which was 3.6 % higher than direct-seeded rice at 84.00 tillers. This trend continued at 60 DAS (250.50 tillers/m^2 vs. 225.20 tillers/m^2, 11.2 % higher), 90 DAS (257.21 tillers/m^2 vs. 232.65 tillers/m^2, 10.6 % higher), 120 DAS (240.20 tillers/m^2 vs. 228.30 tillers/m^2, 5.2 % higher) and at harvest (235.28 tillers/m^2 vs. 220.54 tillers/m^2, 6.7 % higher).

The application of Si significantly influenced the number of tillers, with higher doses of Si resulting in increased tiller production. At 30 DAS, the control (S0) recorded 82.55 tillers/m^2, while 90 kg/ha Si (S3) resulted in 87.87 tillers/m^2 (6.4 % higher). This trend was consistent at subsequent stages, with S3 recording the highest number of tillers at 60 DAS (253.84 tillers/m^2, 14.6 % higher than control), 90 DAS (259.32 tillers/m^2, 13.1 % higher than control), 120 DAS (253.71 tillers/m^2, 17.4 % higher than control) and at harvest (246.43 tillers/m^2, 17.7 % higher than control). The lowest number of tillers was observed in the control (S0) across all stages.

The application of Si solubilizing microbes also influenced the number of tillers, though the differences were not statistically significant. *B. mucilaginosus* (M1) resulted in slightly higher tiller numbers compared to *P. fluorescens* (M2) at all growth stages. For example, at 90 DAS, M1 recorded 247.30 tillers, which was 2.5 % higher than M2 at 241.33 tillers (Fig. 2).

Leaf area index

Among the crop establishment methods, transplanted rice (A2) recorded significantly higher leaf area index (LAI) at all growth stages compared to direct-seeded rice (A1). At 30 DAS, transplanted rice had an LAI of 0.55, which was 31.0 % higher than direct-seeded rice at 0.42. This trend continued at 60 DAS (2.92 vs. 2.15, 35.8 % higher), 90 DAS (3.89 vs. 3.03, 28.4 % higher) and 120 DAS (1.91 vs. 1.42, 34.5 % higher).

The application of Si significantly influenced LAI, with higher doses of Si resulting in increased LAI. At 30 DAS, the control (S0) recorded an LAI of 0.45, while 90 kg/ha Si (S3) resulted in an LAI of 0.51 (13.3 % higher). This trend was consistent at subsequent stages, with S3 recording the highest LAI at 60 DAS (2.75, 23.9 % higher than control), 90 DAS (3.71, 19.7 % higher than control) and 120 DAS (1.87, 37.5 % higher than control). The lowest LAI was observed in the control (S0) across all stages.

The application of Si solubilizing microbes also influenced LAI, though the differences were not statistically significant. *B. mucilaginosus* (M1) resulted in slightly higher LAI compared to *P. fluorescens* (M2) at all growth stages. For example, at 90 DAS, M1 recorded an LAI of 3.46, which was 1.2 % higher than M2 at 3.42 (Fig. 3).

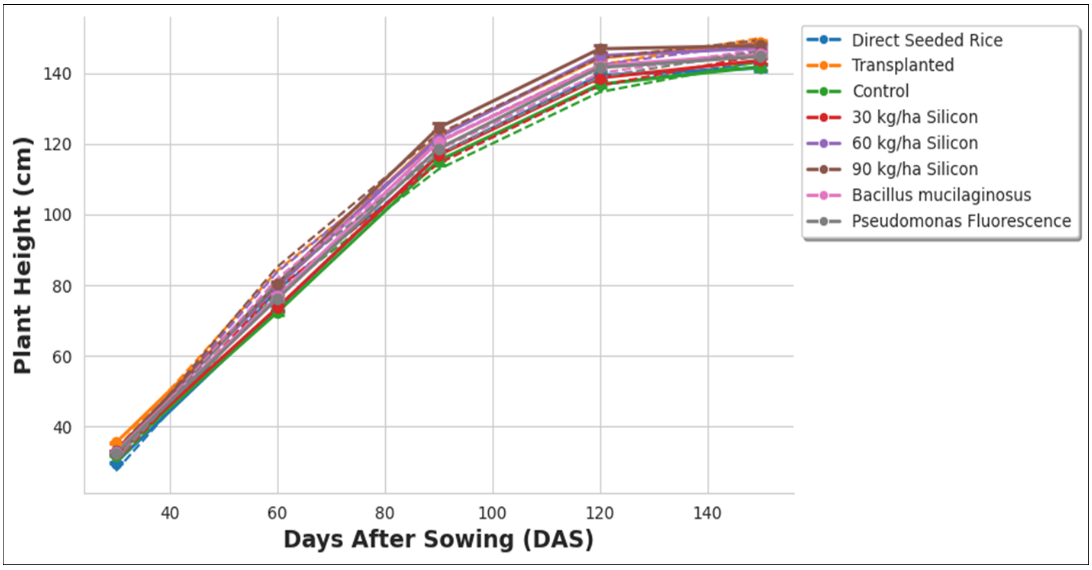

Fig. 1. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on plant height.

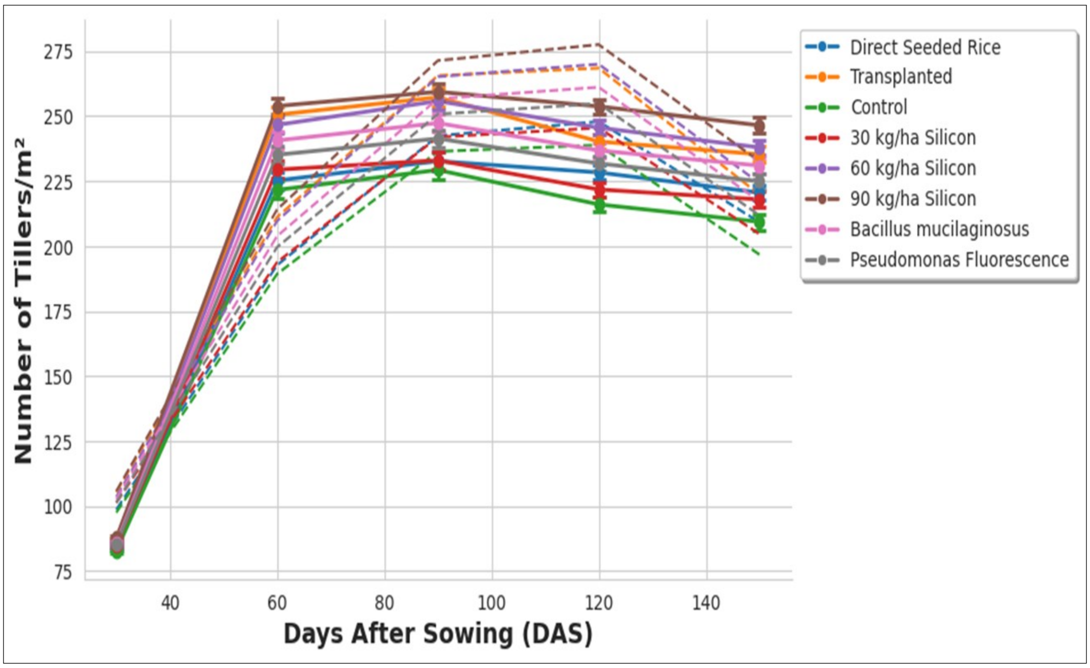

Fig. 2. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on no. of tillers/m^2.

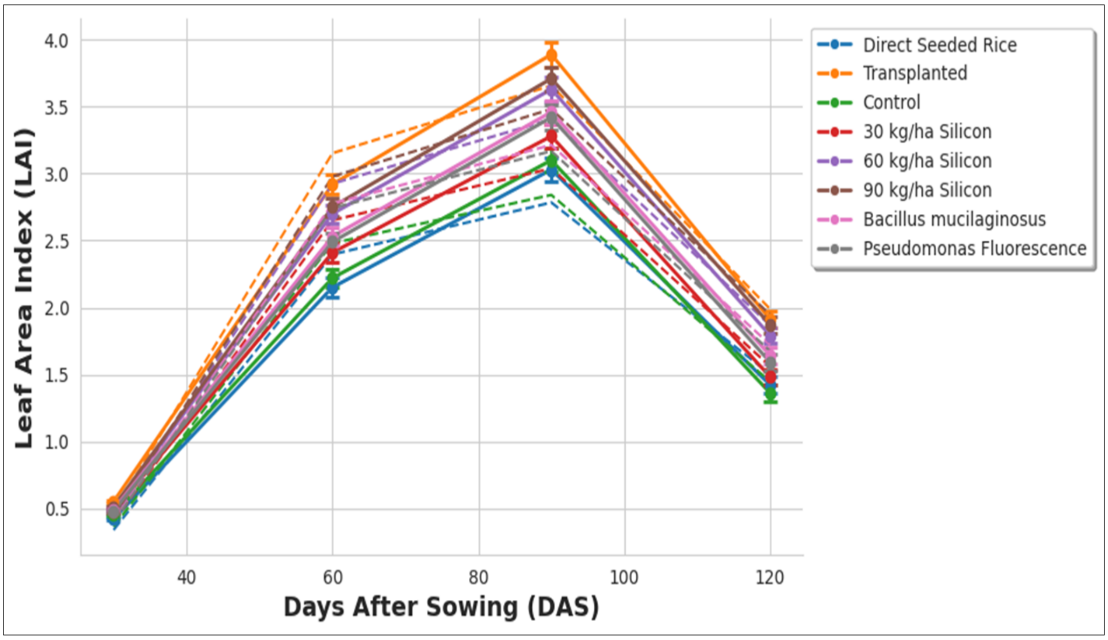

Fig. 3. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on leaf area index.

Dry matter accumulation (g)

Among the crop establishment methods, transplanted rice (A2) recorded significantly higher dry matter accumulation at all growth stages compared to direct-seeded rice (A1). At 30 DAS, transplanted rice had a dry matter accumulation of 132.45 g/m^2, which was 13.9 % higher than direct-seeded rice at 116.32 g/m^2. This trend continued at 60 DAS (272.32 g/m^2 vs. 251.32 g/m^2, 8.4 % higher), 90 DAS (557.32 g/m^2 vs. 530.21 g/m^2, 5.1 % higher), 120 DAS (641.37 g/m^2 vs. 608.32 g/m^2, 5.4 % higher) and at harvest (656.32 g/m^2 vs. 615.20 g/m^2, 6.7 % higher).

The application of Si significantly influenced dry matter accumulation, with higher doses of Si resulting in increased accumulation. At 30 DAS, the control (S0) recorded 118.68 g/m^2, while 90 kg/ha Si (S3) resulted in 130.36 g/m^2 (9.8 % higher). This trend was consistent at subsequent stages, with S3 recording the highest dry matter accumulation at 60 DAS (284.48 g/m^2, 17.8 % higher than control), 90 DAS (564.10 g/m^2, 8.0 % higher than control), 120 DAS (644.30 g/m^2, 6.7 % higher than control) and at harvest (666.01 g/m^2, 10.1 % higher than control). The lowest dry matter accumulation was observed in the control (S0) across all stages.

The application of Si solubilizing microbes also influenced dry matter accumulation, though the differences were not statistically significant. *B. mucilaginosus* (M1) resulted in slightly higher dry matter accumulation compared to *P. fluorescens* (M2) at all growth stages. For example, at 90 DAS, M1 recorded 546.50 g/m^2, which was 1.0 % higher than M2 at 541.00 g/m^2 (Fig. 4).

Crop growth rate ($g/m/day^1$)

Among the crop establishment methods, transplanted rice (A2) recorded significantly higher crop growth rate (CGR) at all growth intervals compared to direct-seeded rice (A1). During 30-60 DAS, transplanted rice had a CGR of 4.66 $g/m^2/day^1$, which was 3.6 % higher than direct-seeded rice at 4.50 $g/m^2/day^1$. This trend continued during 60-90 DAS (9.50 $g/m^2/day^1$ vs. 9.30 $g/m^2/day^1$, 2.2 % higher), 90-120 DAS (2.80 $g/m^2/day^1$ vs. 2.60 $g/m^2/day^1$, 7.7 % higher) and 120-harvest DAS (0.50 $g/m^2/day^1$ vs. 0.26 $g/m^2/day^1$, 92.3 % higher).

The application of Si significantly influenced CGR, with higher doses of Si resulting in increased growth rates. During 30-60 DAS, the control (S0) recorded a CGR of 4.09 $g/m^2/day^1$, while 90 kg/ha Si (S3) resulted in 5.14 $g/m^2/day^1$ (25.7 % higher). This trend was consistent at subsequent intervals, with S3 recording the highest CGR during 60-90 DAS (9.48 $g/m^2/day^1$, 1.7 % higher than control), 90-120 DAS (2.76 $g/m^2/day^1$, 4.2 % higher than control) and 120-harvest DAS (0.72 $g/m^2/day^1$, 414.3 % higher than control). The lowest CGR was observed in the control (S0) across all intervals.

The application of Si solubilizing microbes also influenced CGR, though the differences were not statistically significant. *B. mucilaginosus* (M1) resulted in slightly higher CGR compared to *P. fluorescens* (M2) at all growth intervals. For example, during 60-90 DAS, M1 recorded a CGR of 9.43 $g/m^2/day^1$, which was 0.7 % higher than M2 at 9.36 $g/m^2/day^1$ (Fig. 5).

Yield of basmati rice

Grain yield (kg/ha)

Among the crop establishment methods, transplanted rice (A2) recorded significantly higher grain yield compared to direct-seeded rice (A1). Transplanted rice yielded 3080 kg/ha, which was 16.2 % higher than direct-seeded rice at 2650 kg/ha. The increased yield in transplanted rice can be attributed to better initial crop establishment and resource use efficiency, as indicated by the significantly higher harvest index (39.09 %) compared to direct-seeded rice (36.55 %).

The application of silicon (Si) significantly influenced grain yield. The control (S0) recorded the lowest yield at 2537 kg/ha, while the highest yield of 3167 kg/ha was observed with the application of 90 kg/ha Si (S3), showing a 24.8 % increase over the control. Yield improved progressively with increasing Si levels: 2767 kg/ha at 30 kg/ha (S1) and 2987 kg/ha at 60 kg/ha (S2), reflecting the positive response of rice to silicon fertilization.

The use of Si-solubilizing microbes also affected grain yield, though the differences were not statistically significant. *B. mucilaginosus* (M1) recorded a slightly higher grain yield (2920 kg/ha) compared to *P. fluorescens* (M2) at 2810 kg/ha, representing a 3.9 % improvement. However, these variations did not attain statistical significance, indicating limited influence of microbial treatments on grain yield under the given conditions ((Table 2).

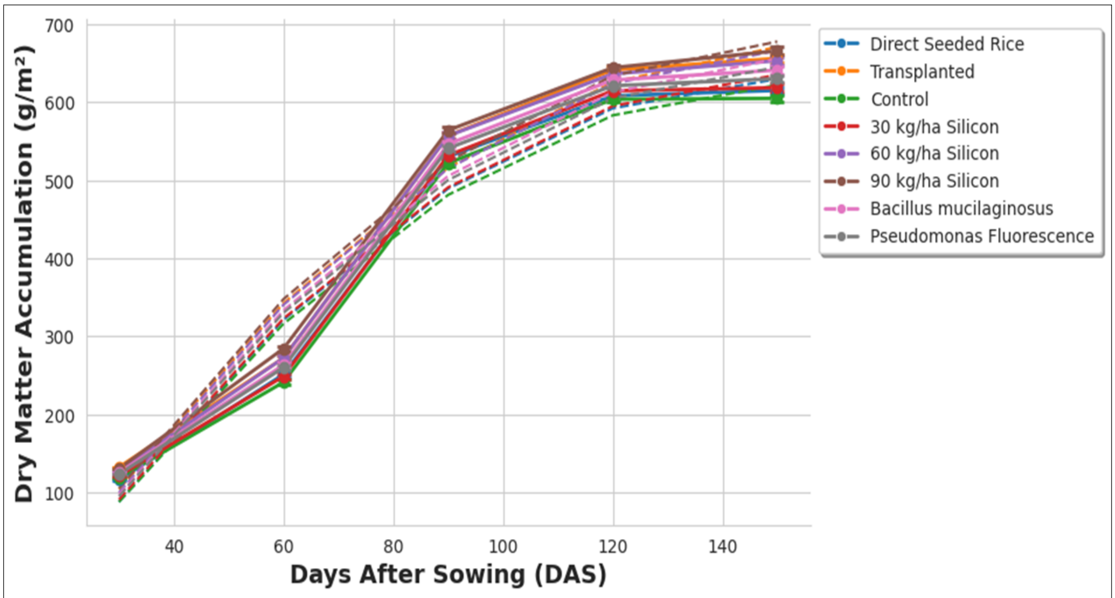

Fig. 4. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on dry matter accumulation.

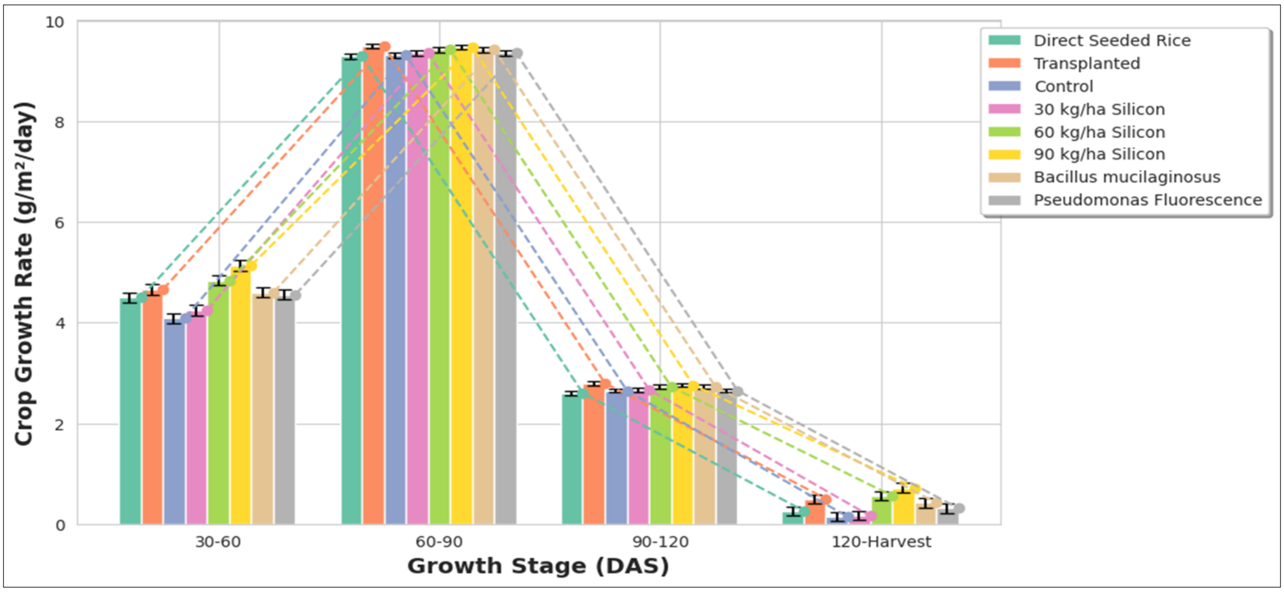

Fig. 5. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on crop growth rate (CGR).

Table 2. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on yield of basmati rice

S. No.	Treatments	Grain yield (kg/ha)	Straw yield (kg/ha)	Harvest index (%)
	Main plot: (Crop establishment)			
A_1	Direct seeded rice	2650	4600	36.55
A_2	Transplanted	3080	4800	39.09
	SEm (±)	128.00	68.50	0.14
	CD (5 %)	380	203	NS
	Sub-plot: (Silicon fertilization)			
S_0	Control	2537	4390	36.62
S_1	30 kg/ha	2767	4590	37.61
S_2	60 kg/ha	2987	4810	38.31
S_3	90 kg/ha	3167	5010	38.73
	SEm (±)	71.00	69.00	0.15
	CD (5 %)	210	205	NS
	Sub-sub-plot: (Silicon solubilizing microbes)			
M_1	Bacillus mucilaginosus (10 g/kg seeds or seedlings)	2920	4750	38.07
M_2	Pseudomonas fluorescens (10 g/kg seeds or seedlings)	2810	4650	37.67
	SEm (±)	35.50	30.00	0.14
	CD (5 %)	NS	NS	NS

Straw yield (kg/ha)

Crop establishment methods had a moderate influence on straw yield. Transplanted rice (A2) recorded a higher straw yield of 4800 kg/ha compared to 4600 kg/ha in direct-seeded rice (A1), marking a 4.3 % increase.

Silicon fertilization significantly enhanced straw yield. The control (S0) registered the lowest straw yield at 4390 kg/ha. A steady increase in straw yield was observed with increasing Si levels: 4590 kg/ha at 30 kg/ha (S1), 4810 kg/ha at 60 kg/ha (S2) and the highest value of 5010 kg/ha at 90 kg/ha Si (S3), which was 14.1 % higher than the control.

The application of Si-solubilizing microbes also had a positive but statistically non-significant effect on straw yield. *B. mucilaginosus* (M1) resulted in a straw yield of 4750 kg/ha, which was 2.2 % higher than *P. fluorescens* (M2) at 4650 kg/ha. While the trend favored M1, the differences did not reach significance under the conditions tested (Table 2).

Harvest index (%)

Harvest index (HI) was influenced by crop establishment methods, with transplanted rice (A2) recording a higher HI of 39.09 % compared to 36.55 % in direct-seeded rice (A1), indicating more efficient partitioning of biomass into economic yield in transplanted rice. However, the difference was not statistically significant.

Silicon application showed an increasing trend in HI with higher doses, though the differences were again not statistically significant. The control (S0) had a HI of 36.62 %, which increased to 37.61 % at 30 kg/ha (S1), 38.31 % at 60 kg/ha (S2) and 38.73 % at 90 kg/ha (S3), showing an overall improvement in harvest efficiency with Si supplementation.

The use of Si-solubilizing microbes did not significantly affect the harvest index. *B. mucilaginosus* (M1) recorded a slightly higher HI of 38.07 % compared to *P. fluorescens* (M2) at 37.67 %. Though numerically higher, these differences were not statistically significant, suggesting a marginal effect of microbial inoculants on biomass partitioning (Table 2).

Economics

Among the crop establishment methods, transplanted rice (A2) recorded significantly higher gross returns, net returns and benefit-cost (B:C) ratio compared to direct-seeded rice (A1). Transplanted rice had a gross return of ₹119623.79/ha, which was 25.2 % higher than direct-seeded rice at ₹95582.44/ha. Net returns for transplanted rice were ₹76485.17/ha, which was 29.3 % higher than direct-seeded rice at ₹59110.02/ha. The B:C ratio for transplanted rice was 1.75, which was 9.4 % higher than direct-seeded rice at 1.60.

The application of Si significantly influenced economic returns, with higher doses of Si resulting in increased gross returns, net returns and B:C ratio. Control (S0) recorded a gross return of ₹85831.88/ha, while 90 kg/ha Si (S3) resulted in a gross return of ₹133994.10/ha (56.1 % higher). Net returns for S3 were ₹89517.58/ha, which was 76.1 % higher than the control at ₹50860.36/ha. The B:C ratio for S3 was 2.00, which was 38.9 % higher than the control at 1.44.

The application of Si solubilizing microbes also influenced economic returns, though the differences were not statistically significant. *B. mucilaginosus* (M1) resulted in slightly higher gross returns, net returns and B:C ratio compared to *P. fluorescens* (M2). M1 recorded a gross return of ₹109691.89/ha, which was 4.0 % higher than M2 at ₹105514.34/ha. Net returns for M1 were ₹69881.87/ha, which was 6.3 % higher than M2 at ₹65713.32/ha. The B:C ratio for M1 was 1.73, which was 6.8 % higher than M2 at 1.62 (Table 3).

Discussion

Transplanted rice (A2) consistently outperformed direct-seeded rice (A1) in terms of plant height, leaf area index (LAI), number of tillers, dry matter accumulation, CGR, grain yield, straw yield and economic returns. The superior performance of transplanted rice can be attributed to better root establishment, reduced competition from weeds and efficient utilization of nutrients and water during the early growth stages (25, 26). Transplanting allows for uniform plant spacing and deeper root penetration, which promotes vigorous vegetative growth and higher yields. Similar findings have been reported (27) who observed that transplanted rice consistently outperformed direct-seeded rice in terms of growth parameters and yield due to better crop establishment and nutrient uptake.

The application of Si significantly enhanced plant height, LAI, tiller number, dry matter accumulation, CGR, grain yield, straw yield and economic returns. Higher doses of Si (90 kg/ha, S3) resulted in the tallest plants, highest LAI, maximum tiller production and greatest dry matter accumulation. Silicon promotes stronger stem development, reduces lodging and enhances resistance to biotic and abiotic stresses, leading to improved crop performance (28). The economic benefits of Si fertilization were also evident, with S3 recording the highest gross returns, net returns and B:C ratio. These findings align with studies (29), who highlighted the role of Si in improving nutrient uptake, stress tolerance and overall crop productivity.

Although the differences were not statistically significant, the application of *B. mucilaginosus* (M1) resulted in slightly higher growth parameters, yield and economic returns compared to *P. fluorescens* (M2). This can be attributed to the ability of *B. mucilaginosus* to solubilize Si more efficiently, making it more available for plant uptake (30). The use of Si solubilizing microbes complements Si fertilization by enhancing Si availability and utilization, leading to improved crop performance. Similar observations were made (31-33), who reported that Si solubilizing microbes enhance nutrient availability and crop growth under rainfed conditions.

Conclusion

Thus, it may be concluded that, transplanted rice combined with 90 kg/ha Si fertilization and *B. mucilaginosus* significantly enhanced growth, yield and economic returns under rainfed conditions. This integrated approach optimized crop performance by improving nutrient uptaketSon. The findings advocate for the adoption of these practices as key strategies to enhance rice productivity and profitability in rainfed agroecosystems.

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Authors' contributions

JSM carried out the research part of the paper. NS carried out the corrections. RK participated in the modification. VG participated in the sequence alignment. CL participated in the table arrangements. FF helped in the rearrangement of the subheadings and finishing. HS helped in arranging the subtopics. GK helped in searching relevant data. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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Table 3. Effect of crop establishment, silicon fertilization and silicon solubilizing microbes on economics

S. No.	Treatments	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	B:C ratio
	Main plot: (Crop establishment)				
A_1	Direct seeded rice	36472.42	95582.4375	59110.0175	1.60
A_2	Transplanted	43138.62	119623.7875	76485.1675	1.75
	Sub-plot: (Silicon fertilization)				
S_0	Control	34971.52	85831.875	50860.355	1.44
S_1	30 kg/ha	38357.52	95714.825	57357.305	1.49
S_2	60 kg/ha	41416.52	114871.65	73455.13	1.77
S_3	90 kg/ha	44476.52	133994.1	89517.58	2.00
	Sub-sub-plot: (Silicon solubilizing microbes)				
M_1	*Bacillus mucilaginosus* (10 g/kg seeds or seedlings)	39810.02	109691.8875	69881.8675	1.73
M_2	*Pseudomonas fluorescens* (10 g/kg seeds or seedlings)	39801.02	105514.3375	65713.3175	1.62

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