PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.6999

eISSN 2348-1900

RESEARCH ARTICLE

Impact of nitrogen levels on crop productivity, farm profitability and nitrogen remobilization of Shahsarang and Mendri varieties of rice

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Received: 01 January 2025; Accepted: 16 January 2025; Available online: Version 1.0: 29 May 2025

Cite this article: Sneha B, Parihar CM, Rathore SS, Das TK, RS Bana, Sunil M, Yeasin Md, Niraj B, Ayan S, Kiranmoy P, Srikanth RK, Badapmain M, Choudhury BU. Impact of nitrogen levels on crop productivity, farm profitability and nitrogen remobilization of Shahsarang and Mendri varieties of rice. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.6999

Abstract

A field study was conducted for rice crops on a lowland rice field of the Indian Council of Agricultural Research (ICAR) Research Complex for the Northeastern Hill Region (NEH), Umiam, Meghalaya, India, during *kharif* 2023. In the present study, five different nitrogen treatments were imposed separately on two varieties - Shahsarang and Mendri, including control, 40 kg N/ha (50 % RDN), 60 kg N/ha (75 % RDN), 80 kg N/ha (100 % RDN) and 100 kg N/ha (125 % RDN). The findings revealed that Shahsarang outperformed Mendri variety in terms of yield attributing characters and biological yield. Nitrogen treatments resulted in 1.1-1.3 times more grains per panicle compared to the control treatments for both varieties. The 100 kg N/ha resulted in the highest biological yield, which was statistically at par with 80 kg N/ha. Conversely, 80 kg N/ha led to the highest vegetative nitrogen remobilization. For both Shahsarang and Mendri, the 80 kg N/ha treatment showed the highest marginal return, approximately 1.3-4 times greater than other treatments. For Shahsarang and Mendri, the net returns were highest under 100 kg N/ha and were at par with 80 kg N/ha. Optimal growth, efficient nitrogen remobilization, the highest marginal return and improved grain yields can be achieved with the appropriate dose of nitrogen, particularly at 80 kg N/ha. These results emphasize the importance of site-specific nitrogen management to enhance both productivity and profitability in rice farming.

Keywords: biological yield; nitrogen doses; puddled transplanted rice; yield attributes

Introduction

Enhancing crop yield is crucial to meet the rising food demand driven by global population growth and increasing incomes. Rice has a pivotal role in global food security and economic stability (1). Any threats to rice production unleash cascading effects across societies, economies and global food systems. More importantly for South Asian countries, rice (*Oryza sativa* L.) is a staple food crop that ensures food and nutritional security in the subcontinent. Specifically emphasizing the north -eastern hill region of India, rice occupies ~80 % of the entire cultivated area with a spread of 3.5 m ha (2). This area is conferred with abundant natural resources, despite these facts the productivity in the region is only about 1.9 t/ha, compared to national averages of 2.8 t/ha (3). Rainfed agriculture in the NEH region is one of the most vulnerable sectors due to the limited availability of land and water resources, subsistence farming and suboptimal use of fertilizers (2). This is compounded by lower nutrient use efficiency due to factors like nitrogen leaching and percolation losses, particularly in high-rainfall regions. Consequently, nitrogen-use efficiency in lowland paddy is very low, typically less than 25 % and it is even lower in sloped upland areas (4). These agro-climatic variables and other physiographic circumstances, such as steep slopes, varied soil types and uneven rainfall distribution, have resulted in significant heterogeneity among rice cultivars in the NEH region, affecting their attainable yields.

Balanced nitrogen fertilization is expected to play a key role in enhancing rice productivity and improving nitrogen-use efficiency, particularly in regions with rice-fallow cropping systems facing nutrient management challenges. By optimizing nitrogen doses, it is possible to achieve higher yields while maintaining soil health and promoting sustainable agricultural practices (5). This study aims to evaluate the effect of varying nitrogen levels on the growth, yield and yield attributes of rice; assess nitrogen-use efficiency under different nitrogen levels; and determine the most effective nitrogen dose for maximizing productivity and sustainability in the rice agroecosystem.

Materials and Methods

Site characteristics

Field experiments were conducted in *Kharif* (May to November) 2023 on a lowland rice field of the Indian Council of Agricultural Research (ICAR) Research Complex for the Northeastern Hill Region (NEH), Umiam, Meghalaya, India (25°41 N; 91°45 E) having an elevation of above 1010 m mean sea level. The experiments involved two rice cultivars: Shahsarang, a high-yielding variety well-suited for lowland areas in mid-altitude regions and Mendri, a locally grown long -duration variety. The experimental field had been under rice monocropping for several years. The experimental site has a clay loam texture with an acidic behaviour. The soil of the study site is an acidic clay loam with a high content of SOC (1.81-2.01 %) and moderate content of available nitrogen (N) (280-284 kg N/ha), potassium (148-174 kg K/ha) and phosphorus (10.7-13.4 kg P/ha).

Weather conditions

The research complex is in a subtropical region and during the rainy season (May to October), the average daily temperature ranges from 23 °C to 32 °C, while in the winter months (November to March), it varies from 13 °C to 20 °C. The southwest monsoon typically starts in July and lasts through September, accounting for 70 % of the annual rainfall, with minimal precipitation from November to March. The total rainfall during the study period was 2220 mm (Fig. 1). The weather data were collected from the meteorological observatory of the research complex.

Details of crop establishment and imposed treatments

The seed rate for both experiments was 35 kg/ha, with a spacing of 20×15 cm^2. The experiments were framed in a Randomized Block Design (RBD), featuring five different nitrogen levels (Control, 50 % RDN-recommended dose of nitrogen, 75 % RDN, 100 % RDN and 125 % RDN). Fertilization management involves the application of nitrogen, phosphorus and potassium in the form of urea, Single Super Phosphate (SSP), diammonium phosphate (DAP) and muriate of potash (MOP). SSP was specifically used for the control treatment. At sowing, half a dose of nitrogen (as per defined treatments) and a full dose of phosphorus and potassium were broadcast. The remaining nitrogen was applied in two equal splits at the maximum tillering and flowering stage, respectively (as per defined treatments). The recommended dose of fertilizers for this region was 80:60:40 kg/ha of N: P_2O_5: K_2O. Weed control was done manually and no pesticides were used throughout the crop season. The crop was grown in a rainfed ecosystem (Fig. 2).

Yield attributes and yield of rice

The number of panicles was counted at harvest and expressed in panicles per square meter. The grains in each panicle were counted from randomly chosen five plants in each net plot, averaged and expressed as the number of grains per panicle. After drying and cleaning, a representative grain sample was taken from the final produce of each net plot and the weight of 1000 grains was recorded and expressed in grams (g). Two border rows in both directions and an additional 0.5 meters along the length were left unharvested. The remaining area of each plot was harvested and the total weight of the harvested produce (total grain + straw) from each net plot was recorded separately after sun/ air drying. This weight was then expressed as biological yield in kg/ha.

Economics

The economic analysis in terms of net return and net benefit: cost ratio (net returns per rupee invested) was computed based on the rate of inputs and output during the study period by considering the incurred variable cost only. Input cost was summed up to calculate the Total Variable Cost (TVC) of the rice crop. The economics of Gross Return (GR) were computed by multiplying the economic output (grain and straw yield of rice) with their respective prices. The Net Return (NR) was worked out by deducting the TVC from GR (NR = GR-TVC). The benefit: cost ratio was worked out by using the following formula:

$$\text{Net B C ratio} = \frac{\text{Net return (₹/ha)}}{\text{Cost of cultivation (₹/ha)}} \quad \text{(Eqn. 1)}$$

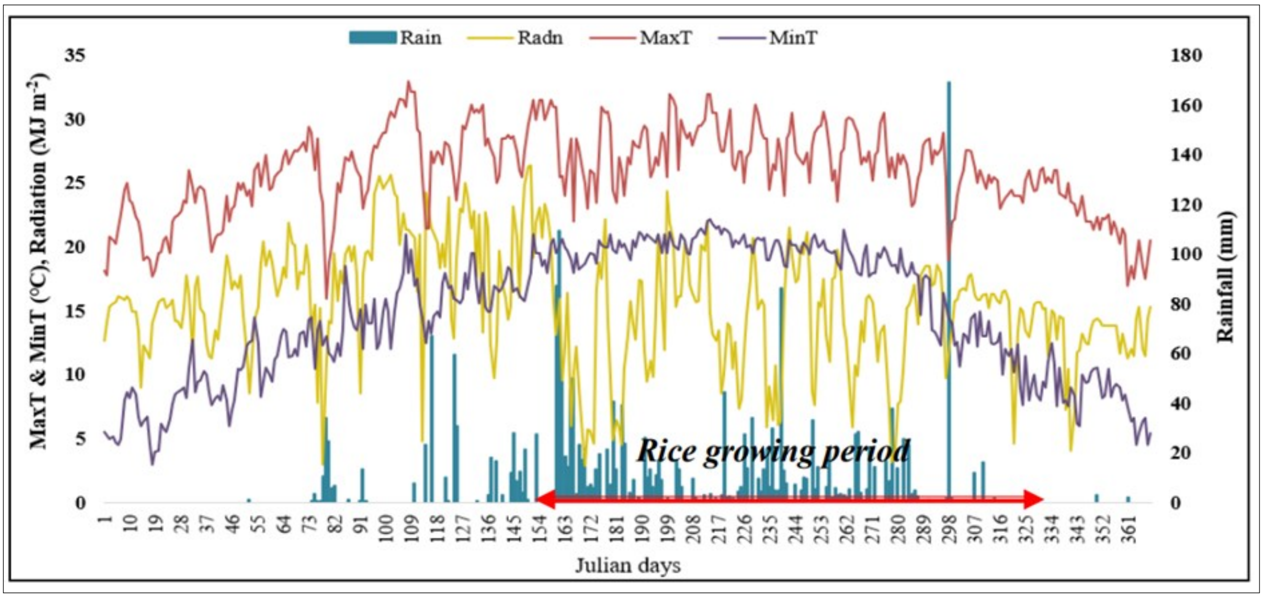

Fig. 1. Daily maximum (Tmax °C) and minimum (Tmin °C) air temperature and solar radiation measured during the growing season.

Marginal return was calculated as the ratio of the increase in net return per additional kg of Nitrogen applied to achieve that return.

Nitrogen content (%) and uptake (kg/ha)

Nitrogen content (N) in grain and straw was determined using the Kjeldahl method as follows (6):

- *N uptake was computed by using the following expression: N uptake (kg/ha) in grain/straw = [% N in grain/straw× grain/straw yield (kg/ha)]* (Eqn. 2)

- *Total uptake of N (kg/ha) = N uptake in grain + N uptake in straw* (Eqn. 3)

Vegetative stage nitrogen uptake and N remobilization

The vegetative stage N uptake (VN) is N accumulated in biomass till the end of the vegetative stage and was calculated by using the following formula:

VN uptake = Total biomass produced till the end of the vegetative stage × N content (%) in biomass

(Eqn. 4)

The remobilized VN into grain was calculated by the balance method (7):

Remobilized VN into grain = VN uptake- Straw N uptake at harvest (Eqn. 5)

Statistical analysis

For statistical analysis, we utilized the latest version (4.3.2) of the R programming (8). Analysis of variance was performed using the aov function of R and differences between means were considered significant at $p < 0.05$ using the Least Significance Difference test (LSD) (9).

Results

Yield attributes and biological yield of Shahsarang and Mendri varieties of rice

The total number of panicles per square meter at harvest significantly varied with different N doses. Shahsarang had the highest panicle count at 125 % RDN (198 panicles/m^2), statistically like 100 % RDN (196 panicles/m^2) but significantly different from other treatments (Table 1). For Mendri, the highest panicle count was recorded under 125 % RDN (194 panicles/m^2), like the 100 % RDN (190 tillers/m^2), while the remaining treatments differed significantly, with the lowest number observed in the control (124 panicles/m^2) (Table 1). Nitrogen application treatments increased the number of panicles per square meter by 19-56 % compared to the control for both varieties (Table 1). Since these varieties had differential production potential, this might have led to variable responses to applied nutrient management practices, leading to variation in yield attributes and yield (10). The study's findings also demonstrated that varying nitrogen doses significantly impacted the total number of grains per panicle (Table 1), as nitrogen is the primary nutrient that limits yield in rice cropping systems globally (11). For Shahsarang, the highest number of grains was achieved under 125 % RDN (120), which was comparable to the results with 100 % RDN (117) and 75 % RDN (113). Similarly, for Mendri, the highest grain count was observed at

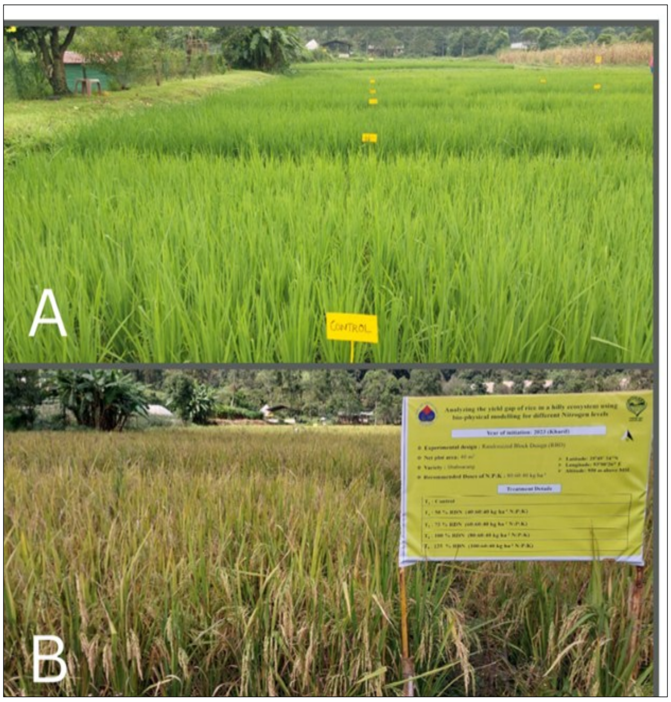

Fig. 2. Rice variety Shahsarang at maximum tillering (A) and physiological maturity (B) at the ICAR-Research complex for the northeastern hill region of India.

125 % RDN (113), closely followed by 100 % RDN (110). Nitrogen treatments resulted in 1.1-1.3 times higher grains/panicle compared to the control treatments for both varieties. Results indicate that an adequate and balanced supply of nitrogen throughout the growing period is crucial for the growth and development of rice. This is characterized by profuse tillering, a satisfactory number of panicles, prolific grain formation and proper grain filling. In the experiment the highest biological yield was observed with the application of 100 kg N/ha under 125 % RDN, yielding 10460 kg/ha for Shahsarang and 8960 kg/ha for Mendri. The lowest biological yields were recorded under the control treatment, with Shahsarang producing 7117 kg/ha and Mendri 6082 kg/ha (Table 1).

Nitrogen application resulted in 1.2 to 1.5 times higher biological yield compared to the control for both Shahsarang and Mendri. The trend in biological yield for both varieties was as follows: 125 % RDN > 100 % RDN > 75 % RDN > 50 % RDN > Control. As per the results, sufficient nitrogen supply helps maintain chlorophyll levels, creating ideal conditions for photosynthesis and biomass accumulation (12). The performance of the rice cultivars comprising of the different yield attributes under variable nitrogen levels was also like the findings elsewhere (13). Moreover, the growth and productivity of a crop are influenced by the interaction between its genetic potential, the environment and management practices. As a result, different varieties exhibit varying performance levels within a specific ecosystem when subjected to a particular set of management practices (14). Regarding HI, no significant difference was observed in the tested treatments under Mendri, as shown in Table 1.

Economics of Shahsarang and Mendri varieties of rice

Among the treatments, variations in the cost of cultivation were observed due to differences in nitrogen levels, as nitrogen is a major input that needs close monitoring.

Table 1. Effect of N levels on yield attributes, yield, HI and economics of Shahsarang (V1) and Mendri (V2) varieties of rice in the northeastern hill region of India

Treatments	Panicle/m^2		Grains/ panicle		Harvest Index (HI)		Biological yield (kg/ha)		Net return (x 10^3 ₹/ha)		Net BC ratio		Marginal return	
	V1	V2	V1	V2	V1	V2	V1	V2	V1	V2	V1	V2	V1	V2
Control	138	124	100	91	34.9	38	7117	6082	26.4	22.3	0.88	0.74	-	-
50 % RDN	164	158	106	99	36.7	39	8607	7212	42.3	33.3	1.43	1.13	398	275
75 % RDN	187	184	113	107	38.5	38	9356	7703	52.1	35.7	1.75	1.2	491	118
100 % RDN	196	190	117	110	41	38	10173	8412	64.6	42.9	2.15	1.43	623	362
125 % RDN	198	194	120	113	41.4	39	10460	8960	67.8	48.5	2.24	1.6	160	278
SEm±	**2.23**	**1.98**	**1.38**	**1.17**	**1.34**	**-**	**189.7**	**150.1**	**3.24**	**2.56**	**0.11**	**0.09**	**-**	**-**
LSD (P=0.05)	**6.88**	**6.09**	**4.26**	**3.59**	**4.12**	**NS**	**584.5**	**462.5**	**10**	**7.9**	**0.33**	**0.26**	**-**	**-**
Mean ± SD	**177 ±23**	**171 ± 27**	**112 ± 8**	**104 ± 9**	**39 ± 3**	**39 ± 1**	**9143 ± 1203**	**7674 ± 995**	**50.6±5.2**	**36.5±8.9**	**1.7±0.5**	**1.2±0.29**	**418±169**	**258±88**

RDN: Recommended dose of nitrogen, V1: Shahsarang and V2: Mendri varieties of rice, SEm: Standard error of the mean, LSD: Least Significant Difference, SD: Standard Deviation

Significantly variable net returns in rice were observed with different nitrogen application treatments and are presented in Table 1. For Shahsarang, the net returns were highest under the 125 % RDN treatment (67784 ₹/ha), which is 2.33 times higher than the control treatment and was at par with the 100 % RDN treatment (64585 ₹/ha). An increase from 75 % to 100 % RDN led to 24 % and 20 % higher net returns for Shahsarang and Mendri, respectively. For the Mendri variety, similar to Shahsarang, the 125 % RDN treatment resulted in the highest net returns (48470 ₹/ha), followed by the 100 % RDN treatment, which had ~2.0 and 1.9 times higher returns compared to the control treatment, respectively. Whereas the lowest net return was observed in the control treatment (22,297 ₹/ha). For the Shahsarang and Mendri genotypes, the application of 125 % and 100 % RDN treatments increased net returns by 20-157 % and 23-117 %, respectively (Table 1). The overall trend of net returns in both rice genotypes (Shahsarang and Mendri) followed the order of 125 % RDN > 100 % RDN > 75 % RDN > 50 % RDN >control (Table 1). The highest Net BC ratio for Shahsarang was observed in the 125 % RDN treatment (2.24), with the lowest ratio recorded in the control treatment (0.88) (Table 1). Similarly, for Mendri, the highest ratio was also in the 125 % RDN treatment (1.6), followed by the 100 % RDN treatment (1.4) and the 75 % RDN treatment (1.2) (Table 1). The control treatment for Mendri had the lowest BC ratio (0.74). The highest marginal return was observed under 100 % RDN for Shahasrang (₹ 623 from each additional unit (kg) of applied N) and Mendri (₹ 362 from each additional unit (kg) of applied N). which follows the law of diminishing returns, indicating that as fertilizer application increases, the return per additional unit of fertilizer decreases. The superiority of the Shahsarang variety in terms of higher productivity owing to higher net return and BC ratio (14). Earlier research has indicated that Shahsarang is particularly suitable for the hill ecosystem of the Eastern Himalayas, India, demonstrating higher productivity and income compared to other varieties (15).

Nitrogen uptake pattern and remobilization of Shahsarang and Mendri varieties of rice

Among the different nitrogen treatments, total nitrogen uptake varied significantly across the different doses for both varieties (Table 2). For Shahsarang, the maximum uptake was observed under the 125 % RDN treatment (86.4 kg/ha), which was comparable to the 100 % RDN treatment (84.2 kg/ha) and the 75 % RDN treatment (77 kg/ha). The control plot (51.6 kg/ ha) and the 50 % RDN treatment (66.5 kg/ha) showed significantly lower from the higher N-dose treatments. Mendri followed a similar uptake pattern, with the highest uptake in the 125 % RDN treatment (72.9 kg/ha), followed by the 100 % RDN treatment (68.4 kg/ha) and the 75 % RDN treatment (61.8 kg/ha), which was like the 50 % RDN treatment (57.7 kg/ha). The lowest uptake was observed in the control plot (46.6 kg/ ha), which was significantly lower than the other treatments (Table 2). For Shahsarang, nitrogen remobilization was highest under 100 % RDN, comparable to 125 % RDN and significantly different from the other treatments (Table 2). Similarly, in Mendri, the highest nitrogen remobilization was observed under 100 % RDN, which was at par with 75 % RDN. The 125 % RDN treatment was like 50 % RDN, both of which differed significantly from the control plot. Reproductive nitrogen levels are notably higher in Mendri compared to Shahsarang (Table 2). Nitrogen treatments significantly influenced reproductive nitrogen levels. For both varieties, 125 % RDN resulted in 3.5–4 times higher than control. Similarly, the 100 % RDN exhibited 3.3 times and 3.7 times higher N uptake at the reproductive stage compared to the control. In terms of vegetative N remobilization, the highest levels were observed under 100 % RDN, with Shahsarang and Mendri showing 13 % and 11 % higher remobilization compared to the control, respectively. Since nitrogen is considered a critical aspect of rice production, its demand-based application becomes the primary driver of productivity. Rice plants absorb nitrogen in their mineralized forms (ammonium and nitrate) indiscriminately, making their availability an important growth factor (16). During the vegetative stage, rice primarily relies on soil mineral nitrogen for uptake, whereas during the reproductive stage, nitrogen uptake is mainly dependent on the organic nitrogen content in plant tissues. This nitrogen is subsequently remobilized towards grain development and seed filling (17) (Table 2).

Despite higher uptake in Mendri, Shahsarang showed greater remobilization efficiency, as it effectively remobilizes nitrogen to the grains. Since remobilization of N from storage pools to sink organs during the reproductive stage is a critical factor for grain nitrogen recovery at harvest (18). Thus, based on the findings of the present study, it can be concluded that understanding the limitations of an agroecosystem is vital in comprehending yield variability. Since nitrogen is a limiting factor in agriculture, its role in improving productivity cannot be overlooked. Therefore, 80 kg N per ha is recommended for both rice varieties. Along with having similar results with 125 % RDN, it has the highest marginal return, which is important from an economic perspective.

Table 2. Effect of nitrogen levels on N remobilization and total N uptake of Shahsarang and Mendri varieties of rice in the northeastern hill region of India

Treatments	Remobilised N (kg/ha)		Reproductive N (kg/ha)		Vegetative N remobilized (%)		Total N uptake (kg/ha)	
	V1	V2	V1	V2	V1	V2	V1	V2
Control	26.1	25.7	2.0	2.4	54.2	52.2	51.6	46.7
50 % RDN	35.9	29.6	4.0	5.9	57.4	56.1	66.5	57.7
75 % RDN	42.9	31.0	4.2	6.3	59.3	57.0	77.0	61.8
100 % RDN	47.1	34.2	7.3	7.8	61.1	58.1	84.2	68.4
125 % RDN	47.7	34.3	8.1	8.3	61.0	58.0	86.4	72.9
SEm±	**2.77**	**1.54**	**1.27**	**0.73**	**2.61**	**2.61**	**2.30**	**1.47**
LSD (P=0.05)	**8.53**	**4.74**	**3.92**	**2.25**	**NS**	**NS**	**7.10**	**4.54**
Mean ± SD	**40 ± 8**	**31 ± 3**	**5 ± 2**	**6 ± 2**	**59 ± 3**	**56 ± 2**	**73 ± 13**	**62 ± 9**

RDN: Recommended Dose of Nitrogen, V1: Shahsarang and V2: Mendri varieties of rice, SEm: Standard error of the mean, LSD: Least Significant Difference, SD: Standard Deviation

Correlation analysis

Correlation analysis revealed significant positive relationships among yield attributes (panicles/m^2, grains/panicle) and nitrogen-related parameters (remobilized nitrogen and total nitrogen uptake) in both rice varieties (Fig. 3). In Shahsarang (V1), correlation coefficients are 0.98 and more, indicating a high degree of physiological coordination between nitrogen utilization and yield component expression. Similarly, Mendri (V2) exhibited strong correlations among the yield attributes, with coefficients ranging from 0.96 to 0.99 (Fig. 3).

Discussion

The growth and productivity of crops are shaped by their genetic potential, environmental factors and management practices. Among these practices, nitrogen (N) is a critical macronutrient for rice. It directly influences photosynthesis, biomass accumulation, protein synthesis, tillering, spikelet formation, grain growth and grain quality (19, 20). Globally, nitrogen is often the key factor limiting rice yields (11). A balanced nitrogen application promotes plant greenness, creating optimal conditions for photosynthesis and biomass production (21). In our study, nitrogen levels significantly impacted rice yields. Increased nitrogen doses improved effective tiller numbers and filled grains per panicle. Split nitrogen applications further enhanced filled grain numbers, which are determined by the number of panicles per hill and grains per panicle. This aligns with the findings of previous study (22). Different rice varieties respond differently to nitrogen levels. For instance, the Shahsarang variety showed the highest yield attributes due to its genetic potential. It maintained a high growth rate, produced more dry matter and effectively translocated this dry matter into grains (23). Shahsarang shows a higher yield than Mendri due to better nitrogen use efficiency and effective nutrient remobilization. It produces more tillers and panicles, contributing to higher biomass and grain yield. Its superior adaptability to hill conditions enhances growth performance. Hence, Shahsarang variety exhibits better resource use and productivity traits. Similar variability among rice varieties has also been observed previously (24). Key factors influencing dry matter production in rice include the number of tillers per unit area, plant height and leaf size. These physical traits depend on adequate nutrient availability, including NPK. In tiller-bearing crops like rice and wheat, differences in production potential across varieties lead to varying responses to nutrient management practices (10).

Rice plants absorb nitrogen in their mineralized forms, primarily ammonium and nitrate, making the soil concentration of these forms vital for plant growth (16). The processes of ammonium assimilation and utilization are complex but crucial for biomass production and grain yield in rice (25). To compensate for lower nitrogen uptake and achieve higher grain yields, additional nitrogen fertilizer is often applied in other crops as well (26). During the vegetative stage, rice mainly depends on soil mineral nitrogen for growth. In the post -anthesis stage, nitrogen is remobilized from plant tissues to support grain development and filling (17). In our study, Mendri

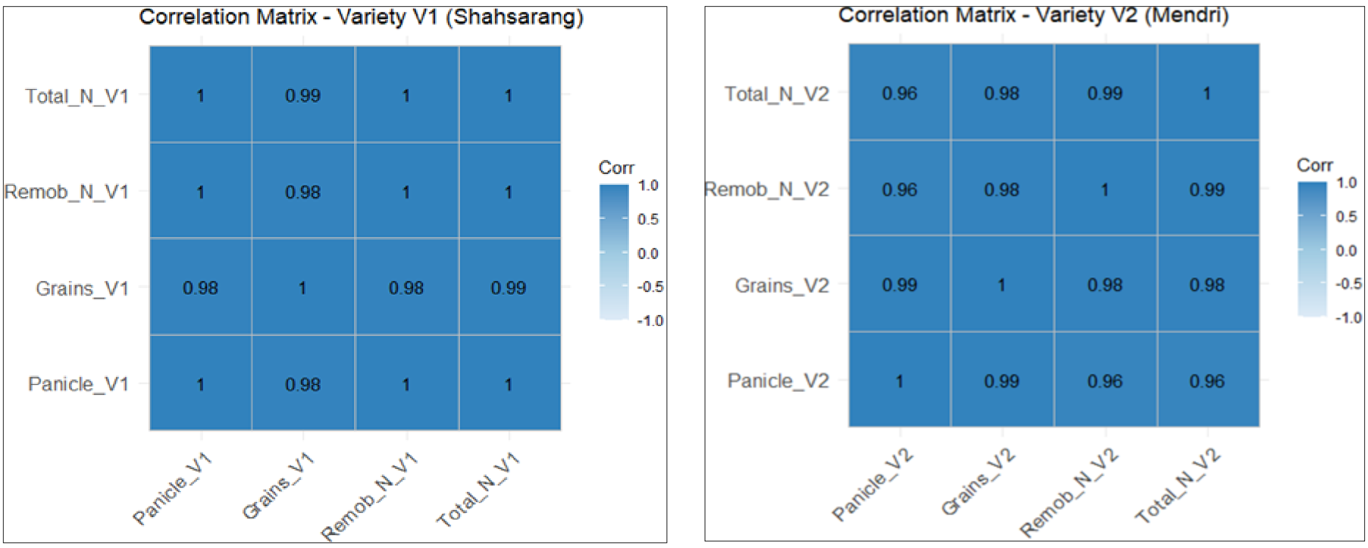

Fig. 3. Correlation matrices for yield attributes and nitrogen parameters in Shahsarang and Mendri rice varieties under different nitrogen treatments.

exhibited higher reproductive nitrogen uptake, while Shahsarang demonstrated greater efficiency in remobilizing nitrogen to grains. This highlights the importance of nitrogen remobilization from storage pools to sink organs, a key factor for grain nitrogen recovery at harvest (18). Enhanced nitrogen assimilation and remobilization during the grain-filling stage contribute significantly to better yield, higher grain nitrogen content and improved protein levels. Nitrogen partitioning during the vegetative stage depends on its availability, while remobilization after anthesis relies on the nitrogen stored in vegetative organs. Greater nitrogen storage in active vegetative parts leads to more effective remobilization during the reproductive stage (27, 28).

The highest marginal return for the Shahsarang and Mendri rice varieties was observed under the 100 % RDN treatment. Shahsarang yielded ₹623 and Mendri ₹362 per additional kilogram of nitrogen applied (compared to 75 % RDN). This follows the law of diminishing returns, where each additional dose of fertilizer produces lower incremental gains as the nitrogen application rate increases. Shahsarang showed superior productivity, reflected in its higher net return and benefit-cost ratio, consistent with previous findings (14). This variety is well-suited for the hill ecosystem of the Eastern Himalayas, offering better productivity and profitability than other varieties (15). Efficient nitrogen management plays a vital role in enhancing nitrogen absorption and increasing the Nitrogen Harvest Index (NHI) at crop maturity in wheat-maize systems (29). The strong positive correlations between nitrogen uptake/remobilization and yield attributes in both Shahsarang and Mendri indicate that nitrogen management is closely related to grain yield in these varieties. The slightly higher correlation values in Shahsarang suggest more efficient coordination between nitrogen use and grain yield, aligning with previous findings that genotypes with better N remobilization tend to perform more consistently under variable nutrient regimes (30). These results also highlight the importance of cultivar selection for enhanced Nitrogen Use Efficiency (NUE) to improve productivity, particularly under sustainable or reduced-input systems.

Conclusion

Based on the findings of this study, it is evident that nitrogen application significantly influences yield attributes, biological yield, nitrogen uptake and economic returns in rice. The application of 125 % RDN resulted in the highest yield attributes and biological yield, while 100 % RDN exhibited the best marginal returns, indicating economic feasibility. Shahsarang outperformed Mendri in terms of productivity and profitability, showcasing its suitability for the hill ecosystem of the Eastern Himalayas. Adequate nitrogen supply, particularly at 80 kg N/ha, is crucial for optimal growth, ensuring efficient nitrogen remobilization and improved grain yield. These findings underscore the importance of precise nitrogen management strategies to sustainably improve productivity and profitability in rice cultivation in Northeastern Hill Region. Future research needs to develop region-specific nitrogen management strategies by integrating indigenous knowledge and precision agriculture to maintain/enhance long-term sustainability, climate resilience and nutrient use efficiency.

Acknowledgements

The first author sincerely acknowledges the Indian Council of Agricultural Research (ICAR), ICAR-Indian Agricultural Research Institute (IARI), for providing the scholarship and other facilities. The research was conducted at ICAR Research Complex for the Northeastern Hill Region (NEH), Umiam, Meghalaya. The support received from the Director and other staff of ICAR RC for NEH region institute, ICAR-IARI, Assam, Division of Agronomy, ICAR-IARI, New Delhi and ICAR-Indian Agricultural Statistics Research Institute (IASRI) is also acknowledged.

Authors' contributions

SB, CMP, and BUC did conceptualization. SB, CMP, SSR, TKD, RSB, SM, NB, AR, KP, KSR, BM and BUC designed the experiments. SB NB, BM and BUC contributed experimental materials. SB executed the field/lab experiments and collected the data. SB, CMP, MY, AR, KP, KSR and BUC performed data analysis and interpretation. SB, CMP, AR, KP, KSR and BUC, prepared the manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration: Authors do not have used generative AI or AI-assisted technologies in writing.

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

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