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RESEARCH ARTICLE

# Screening rice varieties for enhanced nitrogen use efficiency and yield based on root trait evaluation

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## Abstract

Nitrogen (N) fertilizers have played a significant role in enhancing rice yield over recent decades; however, their excessive use has also led to considerable negative environmental impacts. To achieve sustainable productivity, it is essential to adopt strategies that enhance yield while reducing, or at least minimizing, nitrogen input, thereby improving nitrogen use efficiency (NUE). The crucial physiological reasons for maintaining high yield and NUE in N-efficient varieties were attributed to better root system characteristics. Fourteen selected rice varieties, comprising both short-duration and medium-duration varieties, were screened for NUE based on root characteristics under field conditions at two levels of the recommended dose of nitrogen (RDN). Application of 100 % RDN resulted in a significantly higher root volume and Root dry weight. Interaction effects also showed significant influence. Based on the Root Dry Weight Efficiency Index (RDWEI), seven varieties were classified as efficient (RDWEI > 1.0). At the same time, the remaining seven were moderately efficient (RDWEI 0.5-1.0) and none of the varieties were N inefficient (RDWEI <0.5). Trends in RDWEI were consistent with variations in grain yield, highlighting its reliability as a NUE indicator. Among the evaluated varieties, Harsha recorded the highest grain yield (4.1 t ha$^{-1}$), which was statistically comparable to Varsha, Aiswarya and Sreyas. Notably, varieties that maintained stable yields under reduced N application demonstrated superior adaptability and NUE. The study confirmed that genetic variability exists in N response and the interaction between variety and N levels significantly influenced yield and root traits. Identifying N-efficient genotypes with robust root systems presents a promising approach for enhancing N management and promoting sustainable rice production, as well as improved soil health.

**Keywords:** grain yield; nitrogen; nitrogen use efficiency; partial factor productivity of nitrogen; rice; root dry weight efficiency index

## Introduction

Rice (*Oryza sativa* L.) is a primary staple food, sustaining almost half the global population (1). Although it comprises only 2.5 % of the worlds' land area, India supports approximately 18 % of the worlds' population. The ever-growing global population places tremendous pressure on food production, necessitating significant advancements in agricultural output. According to the United Nations' World Population Index, the global population is expected to reach 9.7 billion by 2050, requiring an estimated 60 % increase in food production from the same cultivable land area (2). Mineral fertilizers are crucial for ensuring food security, as more than half of the worlds' food supply relies on their use (3). Among essential plant nutrients, N is the most critical and is frequently a limiting factor in yield across diverse agro-ecological regions (4). Therefore, applying nitrogenous fertilizers is crucial for enhancing productivity in high-input cropping systems.

Modern agriculture has successfully increased grain yields and helped mitigate food shortages (5). However, it has also resulted in excessive accumulation of reactive N, which can exceed environmental thresholds and disrupt critical Earth -system processes (6). On average, crops absorb only about half of the N applied as fertilizer, while about 25 % is lost through leaching, volatilization and denitrification. Due to the low N recovery rate (30-50 %), farmers often apply large amounts of fertilizers to maintain crop productivity, which contributes to increased costs and environmental degradation (7). However, unutilized N contributes to environmental concerns, including water pollution, greenhouse gas emissions and soil degradation (8). These negative consequences impose significant ecological and economic burdens (9). This necessitates the development of N-efficient rice varieties that can maintain productivity under reduced N input, thereby enhancing food security and environmental sustainability.

Although most improved rice varieties are bred under high-input conditions, their NUE is best evaluated under low N availability. There is significant variability among varieties and the interaction between N application rates and variety types influences their performance. Identifying N-efficient varieties and optimized agronomic practices can enhance NUE and support sustainable rice production. A key method for understanding plant responses to varying nitrogen (N) regimes is to examine plants that exhibit superior growth under Nitrogen-Deficient conditions.

The rice root system is vital for several key functions, including the absorption of nutrients and water, the assimilation and synthesis of various compounds and providing structural support to the plants' aboveground parts. Vigorous root growth is crucial, particularly under conditions of nutrient and water stress (10). The root systems' efficiency directly impacts rice growth, development and yield (11). Genotypes with deeper roots are better at absorbing nitrogen from deficient soils (12). Based on this, an ideotype has been proposed that possesses strong lateral roots, deeper rooting and robust nitrate responses to ensure effective nitrogen acquisition in intensive cropping systems (13). Optimizing such root systems can significantly enhance NUE in rice.

This study aimed to evaluate NUE in 14 rice varieties under field conditions, with a focus on root morphological traits to identify genotypes suitable for sustainable rice production. The ability of certain genotypes within a species to absorb nutrients more effectively at low nutrient concentrations in the growth medium is a key mechanism contributing to efficient nutrient use in plants. Traits such as rooting depth, root volume, Root dry weight and Root dry weight efficiency index are key parameters that contribute to improved NUE (14). These traits associated with nitrogen use efficiency can serve as valuable screening criteria for phenotyping and selecting genotypes that are suitable for efficient nitrogen utilization. Such studies accelerate the development of N-efficient rice varieties in breeding programs that focus on enhancing productivity under both optimal and suboptimal N conditions. Supporting this, Research indicates that root morphological characteristics are key determinants of NUE in rice. Identifying nitrogen-efficient rice varieties, combined with optimized agronomic practices, offers a promising strategy to improve NUE and promote sustainable rice production.

## Materials and Methods

The experiment was carried out at the Integrated Farming System Research Station (IFSRS), Karamana, Thiruvananthapuram, during the *Kharif* season of 2023. The primary objective was to screen fourteen selected rice varieties for NUE under field conditions, at two levels of recommended dose of nitrogen (RDN): 70 kg ha$^{-1}$ for short duration and 90 kg ha$^{-1}$ for medium duration rice varieties (16).

The experiment was laid out in a randomized block design with three replications. The fourteen rice varieties were selected based on popularity among the farmers. The varieties included seven short-duration varieties (SDVs), *viz.*, *Makom* (MO 9), *Prathyasa* (MO 21), *KAU Manuratna, Jyothi* (PTB 39*), Harsha* (PTB 55), *Varsha* (PTB 56) and *Kanchana* (PTB 50) and seven medium-duration varieties (MDVs), *viz.*, *Bhadra* (MO 4), *Uma* (MO 16), *Sreyas* (MO 22), *Pournami* (MO 23), *KAU Manuvarna, Athira* (PTB 51) and *Aiswarya* (PTB 52). These varieties were screened for NUE under two N levels: 0 % RDN and 100 % RDN.

The texture of the soil at the experimental site was sandy clay loam, strongly acidic (pH 5.7), low in available N (227.15 kg ha$^{-1}$), medium in available potassium (178 kg ha$^{-1}$) and high in organic carbon (1.25 %) and available phosphorus (33.28 kg ha$^{-1}$). Lime was applied at the rate of 600 kg ha$^{-1}$ in two split doses with 350 kg ha$^{-1}$ at the time of first ploughing and the rest one month after planting). Well-decomposed farmyard manure (FYM) at 5 t ha$^{-1}$ was incorporated during land preparation. The fertilizer recommendations were 70:35:35 kg NPK ha$^{-1}$ for short-duration varieties and 90:45:45 kg ha$^{-1}$ for medium-duration varieties. In the case of short-duration varieties, two-thirds of N, a full dose of P and half of K were applied as basal at the time of transplanting and the remaining one-third of N and half of K were applied one week prior to panicle initiation. In the case of medium-duration varieties, a one-third dose of N, a full dose of P and half the dose of K were applied as basal applications. One-third N was applied at the active tillering stage and one-third N and half the dose of K were applied one week prior to panicle initiation.

The meteorological data collected during the experiment period, including weekly statistics on mean maximum and minimum temperatures, relative humidity and rainfall, were obtained from the Agro-meteorological Observatory of IFSRS, Karamana (Fig. 1). The seedlings of the chosen varieties were raised separately in raised nursery beds and then transplanted into the main field, adopting a spacing of 15 cm × 10 cm for short-duration varieties and 20 cm × 15 cm for medium-duration varieties. Seedlings of short duration and medium duration varieties were transplanted at 18 days and 25 days of age respectively.

### Observations

#### Root parameters

At the harvest stage, six sample hills were carefully uprooted and the following root parameters were measured as per the standard methodology (17).

The root portion was separated, cleaned and the length was measured. The mean value was calculated and recorded in cm. Root volume per plant was estimated using the water displacement method and expressed in cm$^3$ per plant. Root dry weight: The root portion was separated and dried in a hot air oven at (65 ± 5) °C until a constant weight was achieved, then measured and recorded in grams (g). Root dry weight efficiency index (RDWEI): After drying the plant material at (65 ± 5) °C the roots were weighed and the correlation between Root dry weight efficiency index (RDWEI) and yield was analyzed. RDWEI was calculated by using the formula (18),

$$\text{RDWEI} = \frac{\text{Root dry wt. at low N rate}}{\text{Average Root dry wt. of genotypes at low N rate}} \times \frac{\text{Root dry wt. at High N rate}}{\text{Average Root dry wt. of genotypes at High N rate}} \quad \text{(Eqn. 1)}$$

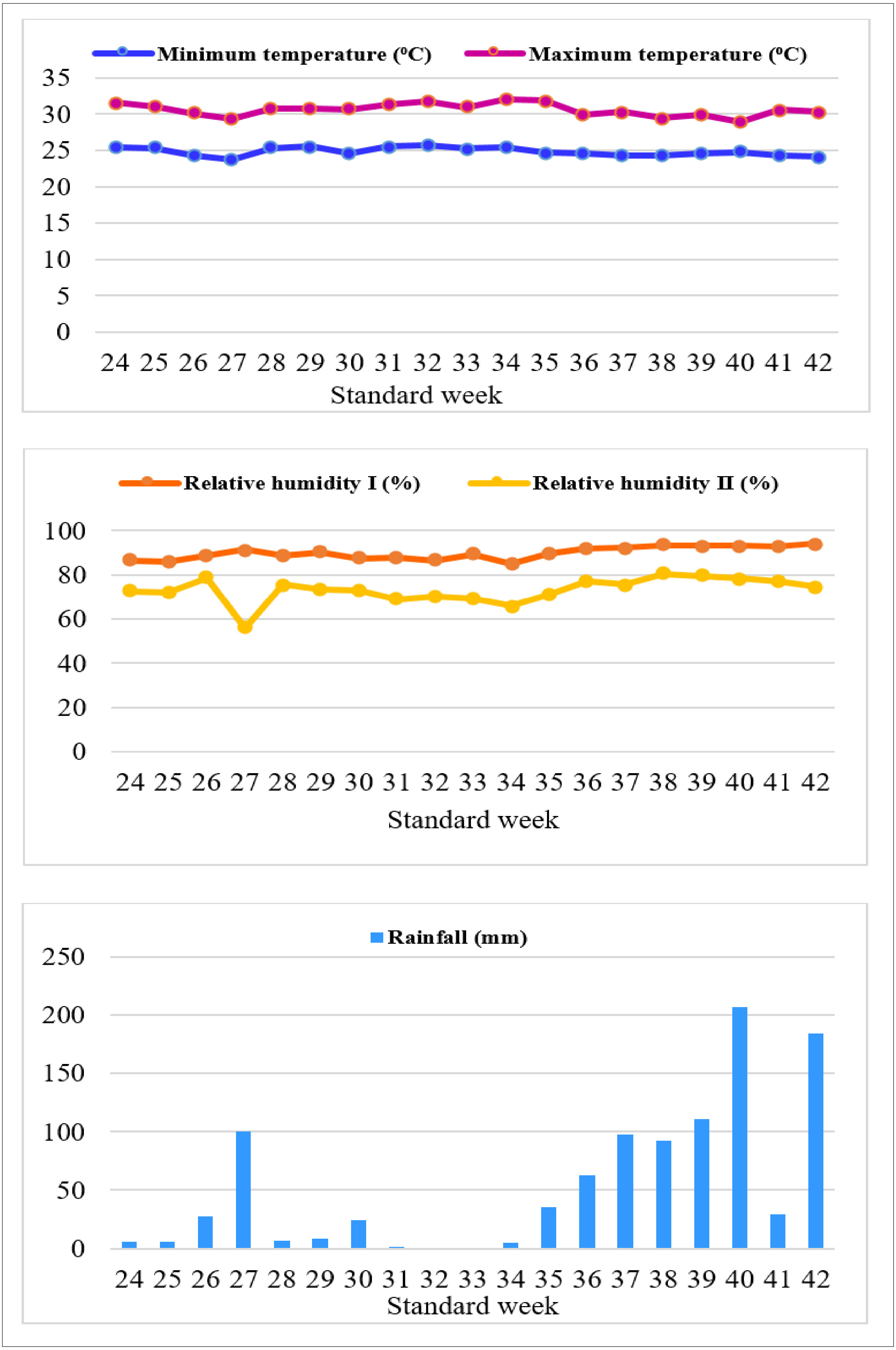


**Fig. 1.** Standard week wise weather parameters during the cropping period (11 June 2023 to 21 Oct' 23)

Genotypes with RDWEI values greater than 1.0 were regarded as efficient, while those ranging from 0.5 to 1.0 were categorized as moderately efficient and genotypes with RDWEI values below 0.5 were identified as inefficient in N utilization.

**Grain yield:** The net plot area was harvested separately, threshed, grains cleaned and dried to a moisture level of 14 %. The final grain weight was measured and expressed in kg $ha^{-1}$.

**Partial factor productivity of N ($PFP_N$):** $PFP_N$ was worked out by using the formula and expressed as kg yield per kg nutrient applied (19). PFP reflects how effectively the applied N is utilized by the crop to produce yield.

**PFP** = crop yield with applied nutrients / fertilizer rate (Eqn. 2)

**Harvest index:** Harvest index was calculated as the ratio between economic yield (grain yield) and biological yield (grain yield + straw yield (20).

### Statistical Analysis

Data from the different treatments were analyzed using standard ANOVA procedures. The GRAPES program, developed by the Department of Agricultural Statistics at the College of Agriculture, Vellayani, was used to analyze and compare the treatments (21). The F test was used to evaluate statistical significance (22). For cases where the F test indicated significance, the critical difference (CD) was calculated and reported.

## Results and Discussion

### Rooting depth

The rooting depth showed significant variation among the rice varieties and between the N levels tested (Table 1 and Fig. 2). Among the SDVs, Harsha recorded the deepest roots (26.31 cm), which was 28.40 % greater than that of KAU Manuratna, the variety with the lowest rooting depth (20.49 cm).

**Table 1.** Effect of varieties and nitrogen levels on root parameters of rice

| Treatments | Rooting depth (cm) | Root volume ($cm^3$) | Root dry weight (g/ plant) |
|---|---|---|---|
| $v_1$- Makom (MO 9) | 22.73 | 9.30 | 5.49 |
| $v_2$- Prathyasa (MO 21) | 21.91 | 9.05 | 5.24 |
| $v_3$- KAU Manuratna | 20.49 | 9.18 | 5.74 |
| $v_4$- Jyothi (PTB 39) | 24.04 | 8.98 | 5.25 |
| $v_5$- Harsha (PTB 55) | 26.31 | 10.28 | 5.86 |
| $v_6$- Varsha (PTB 56) | 24.17 | 10.00 | 5.97 |
| $v_7$- Kanchana (PTB 50) | 22.29 | 9.45 | 5.59 |
| $v_8$- Bhadra (MO 4) | 22.53 | 8.55 | 4.58 |
| $v_9$- Uma (MO 16) | 22.84 | 9.38 | 5.73 |
| $v_{10}$- Sreyas (MO 22) | 24.87 | 10.40 | 6.31 |
| $v_{11}$- Pournami (MO 23) | 20.90 | 8.68 | 4.89 |
| $v_{12}$- KAU Manuvarna | 21.53 | 9.43 | 5.51 |
| $v_{13}$- Athira (PTB 51) | 24.78 | 9.55 | 5.92 |
| $v_{14}$- Aiswarya (PTB 52) | 27.08 | 11.05 | 6.51 |
| SE m (±) | 0.26 | 0.139 | 0.092 |
| CD (0.05) | 0.754 | 0.404 | 0.266 |
| **Levels of nitrogen (N)** | | | |
| $n_0$- 0 % RDN | 24.07 | 8.65 | 4.98 |
| $n_1$- 100 % RDN | 22.57 | 10.39 | 6.24 |
| SE m (±) | 0.10 | 0.05 | 0.04 |
| CD (0.05) | 0.285 | 0.153 | 0.101 |
| **Interaction (V× N)** | | | |
| $v_1n_0$ | 23.94 | 8.35 | 4.79 |
| $v_1n_1$ | 21.53 | 10.25 | 6.20 |
| $v_2n_0$ | 20.84 | 7.95 | 4.49 |
| $v_2n_1$ | 22.99 | 10.15 | 5.99 |
| $v_3n_0$ | 21.21 | 8.25 | 5.13 |
| $v_3n_1$ | 19.76 | 10.10 | 6.35 |
| $v_4n_0$ | 24.18 | 7.95 | 4.68 |
| $v_4n_1$ | 23.91 | 10.00 | 5.83 |
| $v_5n_0$ | 27.20 | 9.80 | 5.23 |
| $v_5n_1$ | 25.43 | 10.75 | 6.49 |
| $v_6n_0$ | 25.60 | 9.45 | 5.25 |
| $v_6n_1$ | 22.74 | 10.55 | 6.69 |
| $v_7n_0$ | 24.25 | 8.35 | 4.88 |
| $v_7n_1$ | 20.33 | 10.55 | 6.31 |
| $v_8n_0$ | 21.39 | 7.60 | 4.26 |
| $v_8n_1$ | 23.66 | 9.50 | 4.89 |
| $v_9n_0$ | 23.84 | 8.35 | 4.95 |
| $v_9n_1$ | 21.85 | 10.40 | 6.50 |
| $v_{10}n_0$ | 27.03 | 9.80 | 5.65 |
| $v_{10}n_1$ | 22.71 | 11.00 | 6.96 |
| $v_{11}n_0$ | 21.83 | 7.75 | 4.51 |
| $v_{11}n_1$ | 19.98 | 9.60 | 5.26 |
| $v_{12}n_0$ | 21.75 | 8.25 | 4.78 |
| $v_{12}n_1$ | 21.30 | 10.60 | 6.25 |
| $v_{13}n_0$ | 25.86 | 8.55 | 5.25 |
| $v_{13}n_1$ | 23.70 | 10.55 | 6.59 |
| $v_{14}n_0$ | 28.13 | 10.65 | 5.93 |
| $v_{14}n_1$ | 26.04 | 11.45 | 7.10 |
| SE m (±) | 0.37 | 0.20 | 0.13 |
| CD (0.05) | 1.067 | 0.571 | 0.376 |

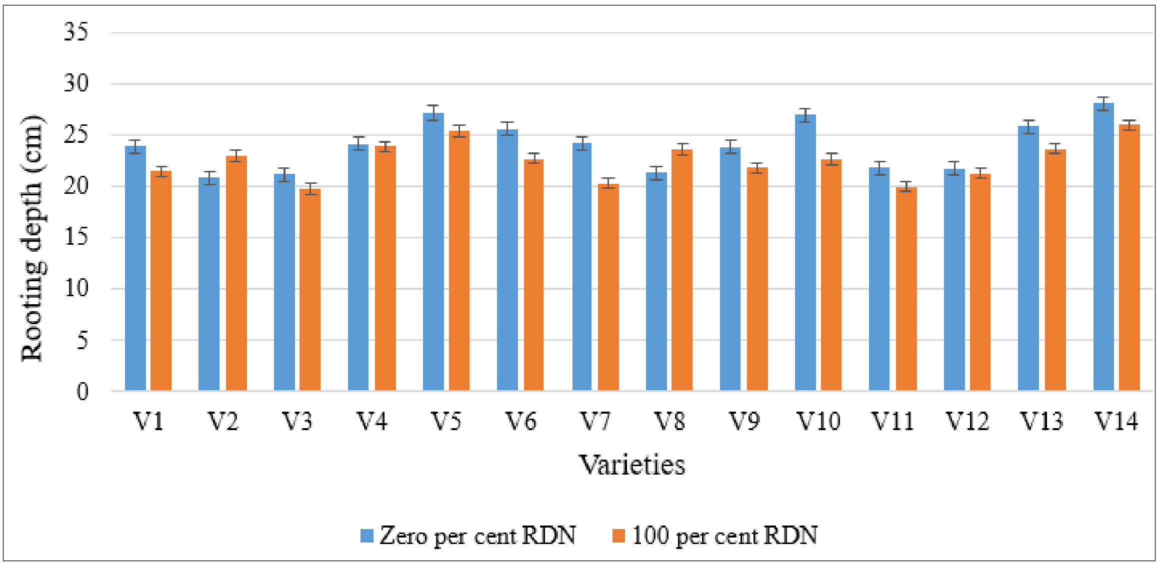


**Fig. 2.** Interaction effect of varieties and levels of nitrogen on rooting depth of rice

Meanwhile, among the MDVs, Aiswarya exhibited the deepest roots (27.08 cm), which was 29.57 % greater than that of Pournami (20.90 cm). This implies different rice varieties exhibit varying levels of adaptability to N stress (23).

Concerning levels of N, zero % RDN resulted in significantly deeper roots (24.45 cm), representing a 6.65 % increase compared to 100 % RDN. Under N-deficient conditions, rice plants often exhibit increased root length as an adaptive response to enhance nutrient acquisition. This is a common adaptive response in N-efficient cultivars, where greater root length supports better N uptake under nutrient-limited conditions. Whereas, root length may decrease when N is readily available in the soil, reducing the need for plants to develop extensive root systems. Research indicates that rice varieties with high nitrogen uptake efficiency exhibit superior root traits, including increased root biomass, length and volume, even under nitrogen-deficient conditions, as an adaptive strategy to enhance nutrient acquisition (24, 25). The interaction effect further revealed that among the SDVs, Harsha under zero % RDN produced deeper roots (27.2 cm), while among MDVs, *Aiswarya* under zero % RDN produced deeper roots (28.13 cm). Both were on par, surpassing all other variety and N-level combinations.

## Root volume

Harsha recorded a higher root volume (10.28 $cm^3$among the SDVs, which was comparable to Varshas' (10 $cm^3$). Meanwhile, among the MDVs, Aiswarya recorded the highest root volume (11.05 $cm^3$), which was 29.24 % greater than that of Bhadra, the variety with the lowest root volume (8.55 $cm^3$). This variation highlights the genetic potential of certain varieties to develop more robust root systems under optimal N conditions. Research indicates that rice varieties with improved NUE exhibit enhanced root development, contributing to better nutrient uptake and higher productivity (26). Among the N levels, root volume increased by 20.12 % under 100 % RDN, indicating the positive influence of adequate N availability on root development. This enhancement can be attributed to the role of nitrogen in promoting cell division and elongation in the Root apical meristem, thereby stimulating root expansion, branching and overall biomass accumulation. Research indicates that mild N deficiency can stimulate root growth, aiding in deeper root penetration to improve nitrogen foraging. An adequate N supply enhances critical root traits, such as root number, biomass and density, providing a balance between root expansion and functional efficiency (27).

The interaction effect further emphasized this trend. Among SDVs Harsha (10.75 $cm^3$) under 100 % RDN recorded higher root volume, which was on par with Varsha (10.55 $cm^3$) and Kanchana (10.55 $cm^3$) under 100 % RDN. Among the MDVs, Aiswarya under 100 % RDN recorded a higher root volume (11.45 $cm^3$) which was comparable to that of Sreyas under 100 % RDN (11 $cm^3$) (Table 1). Overall, the findings on rooting depth and root volume suggest that an increase in root length is an adaptive strategy for coping with N deficiency. However, since N is a crucial nutrient, prolonged and severe N deprivation, such as the zero N treatment, suppresses adventitious root formation and reduces the total root system volume (25).

## Root dry weight

Significant variations were observed among the rice varieties and N levels in terms of Root dry weight (Table 1). Among the SDVs, Varsha recorded a higher Root dry weight (5.97 g), which was comparable to that of Harsha and KAU Manuratna. Similarly, among the MDVs, Aiswarya recorded a higher Root dry weight (6.51 g), which was comparable to that of Sreyas (6.30 g). In contrast, Bhadra exhibited the lowest Root dry weight (4.58 g), indicating its relatively lower ability to develop a robust root system and suggesting lower nitrogen use efficiency.

N levels had a pronounced effect, with 100 % RDN application resulting in a Root dry weight of 6.24 g, which was 25.30 % higher than that observed under 0 % RDN. This highlights the critical role of adequate N in promoting root biomass development. Adequate nitrogen facilitates the development of a more vigorous root system, which serves as a foundation for improved nutrient uptake and plant growth.

The interaction effect further supported these findings, as Varsha under 100 % RDN recorded the highest Root dry weight (6.69 g) among the SDVs, while Aiswarya under 100 % RDN recorded the highest Root dry weight among the MDVs, which was statistically on par with $v_{10}n_1$. Research indicates that applying optimal N levels significantly enhances Root dry weight (28). This highlights the importance of robust root traits in enhancing NUE and increasing grain yield in rice.

## Root dry weight efficiency index

The analysis of RDWEI revealed that half of the varieties were efficient in N use, while the remaining half were moderately efficient (Fig. 3). Notably, none of the varieties could be categorized as inefficient in N use. The efficient N use genotypes included, Aiswarya ($v_{14}$) (1.37), Sreyas ($v_{10}$) (1.26), Varsha ($v_6$) (1.23), Harsha ($v_5$) (1.18), Athira ($v_{13}$) (1.14), KAU Manuratna ($v_3$) (1.13), Kanchana ($v_7$) (1.07), Uma ($v_9$) (1.04) and Makom ($v_1$) (1.03). While the moderately efficient genotypes were KAU Manuvarna ($v_{12}$) (0.95), Prathyasa ($v_2$) (0.95), Jyothi ($v_4$) (0.94), Bhadra ($v_8$) (0.69) and Pournami ($v_{11}$) (0.67). The trends observed in RDWEI closely mirrored those in total grain weight, indicating a strong correlation between NUE and productivity, reinforcing its use as a selection criterion. This finding aligns with recent studies demonstrating that N-efficient varieties (NEVs) outperform N-inefficient varieties (NIVs) in terms of grain yield and NUE (29). The enhanced performance of NEVs is attributed to their superior root and shoot activity (30). Furthermore, a robust root system is crucial for sustaining plant growth and development, ultimately leading to higher yields (31).

## Grain yield

Table 2 presents data on grain yield as influenced by variety and nitrogen levels. Among the SDVs, *Harsha* recorded a higher grain yield (4.1 t $ha^{-1}$), Among the MDVs, Aiswarya recorded the highest grain yield (3.93 t $ha^{-1}$) which was on par with Sreyas (3.80 t $ha^{-1}$). The grain yield of all four varieties was comparable, demonstrating their superior ability to utilize available nitrogen efficiently (32). Research indicates that nitrogen-efficient varieties (NEVs) outperform nitrogen-inefficient varieties (NIVs) in grain yield and NUE, owing to their superior root and shoot activity (30, 33). The positive correlation observed between root traits and grain yield further supports the hypothesis that robust root systems are integral to improving NUE. For instance, varieties with higher Root dry weight and root volume showed better grain yield performance under both N regimes. Research indicates that enhanced root biomass and length directly influence nitrogen (N) uptake and utilization efficiency (34).

N levels significantly influenced grain yield, with the application of 100 % RDN resulting in a yield of 3.74 t $ha^{-1}$, an 83.33 % increase compared to 0 % RDN (2.04 t $ha^{-1}$). Research indicates thatst longer root length as a critical trait in rice varieties achieving high grain yield and improved NUE, particularly under N-limited conditions or reduced N application rates (32). Additionally, research indicates that the advantage of long root systems in accessing nitrogen (N) from deeper soil layers makes this an ideal trait for enhancing N acquisition (35).

The combined effect of variety and N level on grain yield was most pronounced for Harsha under 100 % RDN (4.75 t $ha^{-1}$) among the SDVs, which was statistically on par with $v_6n_1$ and $v_3n_1$. Among the MDVs, Aiswarya under 100 % RDN (4.65 t $ha^{-1}$), recorded higher grain yield which was comparable to $v_{10}n_1$ (4.60 t $ha^{-1}$) (Fig. 4). The grain yield of high performing SDVs and MDVs were also statistically comparable. The least reduction in grain yield with $n_o$ compared to $n_{100}$ was observed in $v_6$, $v_5$, $v_{14}$ and $v_{10}$ (23.9, 27.4, 31.2 and 34.8 % respectively) indicating that these varieties maintained relatively stable yield performance even under 0 % RDN compared to 100 % RDN. Research indicates thatgreater root biomass and root length are correlated with enhanced grain yield and NUE, including indices such as N harvest index and partial factor productivity of applied N.

## Straw yield

The data on straw yield indicated that, *Harsha* recorded higher straw yield (7.83 t $ha^{-1}$), among the SDVs, which was statistically comparable with Varsha (7.72 t $ha^{-1}$). Among MDVs, Aiswarya recorded the highest straw yield (6.76 t $ha^{-1}$).

N levels also had a significant impact, with 100 % RDN leading to a 53.86 % increase in straw yield compared to zero % RDN. This demonstrates that increasing N levels promotes biomass accumulation, as supported by previous research (37, 38). Research indicates that N application significantly enhances tiller number and dry matter production, contributing to increased straw yield. The interaction effect showed that among SDVs, KAU Manuratna under 100 % RDN recorded higher straw yield, which was statistically comparable to $v_5n_1$, $v_6n_1$, $v_1n_1$ and $v_7n_1$. Meanwhile, among MDVs, Aiswarya, under 100% RDN, recorded a higher straw yield, which was on par with Sreyas, under 100% RDN.

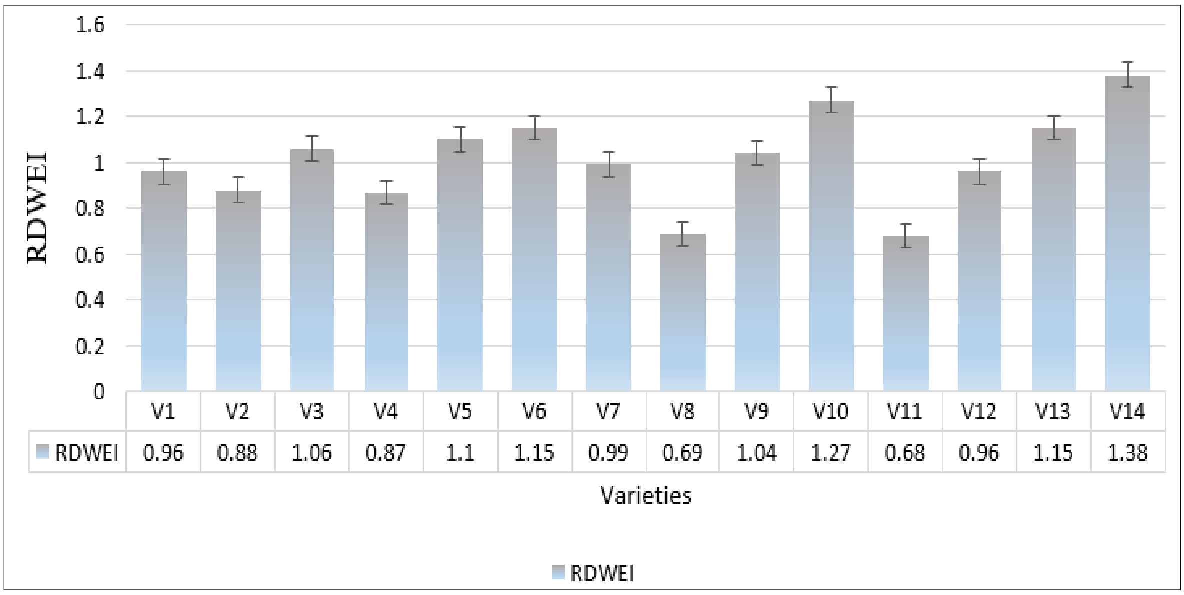


**Fig. 3.** Effect of varieties on root dry weight efficiency index of rice

**Table 2.** Effect of varieties and nitrogen levels on grain yield, straw yield and harvest index of rice

| Treatments | Grain yield (tonnes $ha^{-1}$) | Straw yield (tonnes $ha^{-1}$) | Harvest Index |
|---|---|---|---|
| $v_1$- Makom (MO 9) | 2.35 | 5.40 | 0.29 |
| $v_2$- Prathyasa (MO 21) | 2.48 | 5.64 | 0.30 |
| $v_3$- KAU Manuratna | 2.90 | 6.41 | 0.31 |
| $v_4$- Jyothi (PTB 39) | 2.80 | 6.09 | 0.31 |
| $v_5$- Harsha (PTB 55) | 4.10 | 7.83 | 0.34 |
| $v_6$- Varsha (PTB 56) | 4.05 | 7.72 | 0.34 |
| $v_7$- Kanchana (PTB 50) | 2.63 | 5.99 | 0.30 |
| $v_8$- Bhadra (MO 4) | 2.18 | 4.54 | 0.31 |
| $v_9$- Uma (MO 16) | 2.78 | 5.79 | 0.32 |
| $v_{10}$- Sreyas (MO 22) | 3.80 | 6.51 | 0.37 |
| $v_{11}$- Pournami (MO 23) | 2.23 | 5.00 | 0.30 |
| $v_{12}$- KAU Manuvarna | 1.95 | 4.23 | 0.31 |
| $v_{13}$- Athira (PTB 51) | 2.33 | 4.86 | 0.32 |
| $v_{14}$- Aiswarya (PTB 52) | 3.93 | 6.76 | 0.37 |
| SE m (±) | 0.16 | 0.36 | 0.01 |
| CD (0.05) | 0.470 | 1.043 | 0.020 |
| **Levels of nitrogen (N)** | | | |
| $n_0$- 0 % RDN | 2.04 | 4.66 | 0.30 |
| $n_1$- 100 % RDN | 3.74 | 7.17 | 0.34 |
| SE m (±) | 0.06 | 0.14 | 0.003 |
| CD (0.05) | 0.179 | 0.394 | 0.008 |
| **Interaction (V× N)** | | | |
| $v_1n_0$ | 1.10 | 3.01 | 0.27 |
| $v_1n_1$ | 3.60 | 7.80 | 0.32 |
| $v_2n_0$ | 1.70 | 4.87 | 0.26 |
| $v_2n_1$ | 3.25 | 6.42 | 0.34 |
| $v_3n_0$ | 1.50 | 3.85 | 0.29 |
| $v_3n_1$ | 4.30 | 8.97 | 0.33 |
| $v_4n_0$ | 2.10 | 5.52 | 0.28 |
| $v_4n_1$ | 3.50 | 6.67 | 0.35 |
| $v_5n_0$ | 3.45 | 7.02 | 0.33 |
| $v_5n_1$ | 4.75 | 8.64 | 0.36 |
| $v_6n_0$ | 3.50 | 7.22 | 0.32 |
| $v_6n_1$ | 4.60 | 8.22 | 0.36 |
| $v_7n_0$ | 1.70 | 4.24 | 0.29 |
| $v_7n_1$ | 3.55 | 7.75 | 0.32 |
| $v_8n_0$ | 1.10 | 2.65 | 0.29 |
| $v_8n_1$ | 3.25 | 6.44 | 0.34 |
| $v_9n_0$ | 2.05 | 4.61 | 0.31 |
| $v_9n_1$ | 3.50 | 6.98 | 0.34 |
| $v_{10}n_0$ | 3.00 | 5.67 | 0.35 |
| $v_{10}n_1$ | 4.60 | 7.35 | 0.39 |
| $v_{11}n_0$ | 1.35 | 3.48 | 0.28 |
| $v_{11}n_1$ | 3.10 | 6.52 | 0.32 |
| $v_{12}n_0$ | 1.15 | 3.06 | 0.28 |
| $v_{12}n_1$ | 2.75 | 5.39 | 0.34 |
| $v_{13}n_0$ | 1.65 | 3.92 | 0.30 |
| $v_{13}n_1$ | 3.00 | 5.80 | 0.34 |
| $v_{14}n_0$ | 3.20 | 6.11 | 0.35 |
| $v_{14}n_1$ | 4.65 | 7.41 | 0.39 |
| SE m (±) | 0.23 | 0.51 | 0.01 |
| CD (0.05) | 0.670 | 1.475 | NS |

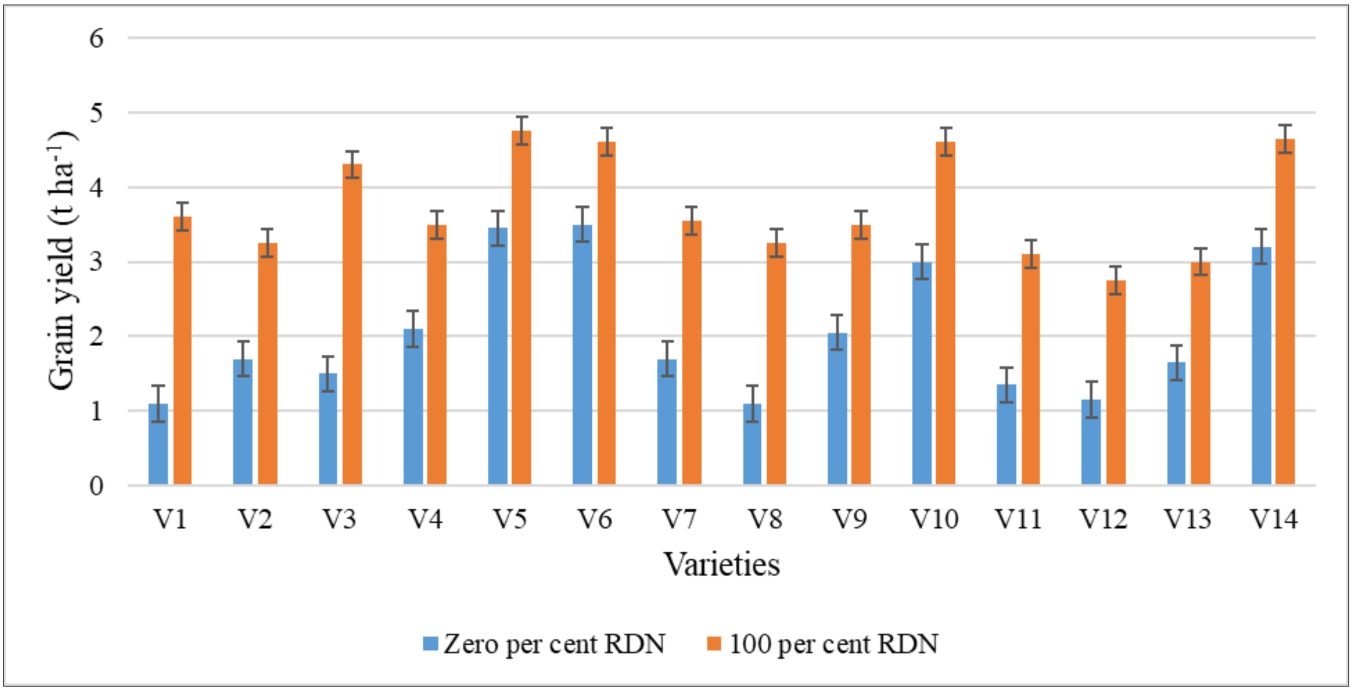


**Fig. 4.** Interaction effect of varieties and levels of nitrogen on grain yield of rice

## Partial factor productivity of nitrogen

The data presented in Fig. 5 reveal significant variation in the $PFP_N$ among the rice varieties under 100 % RDN. Specifically, among the SDVs, higher PFP value was recorded for Harsha (68.09 kg kg$^{-1}$ N applied) which was on par with Varsha (65.95 kg kg$^{-1}$ N applied) and KAU Manuratna (61.18 kg kg$^{-1}$ N applied), indicating their superior NUE. Among the MDVs, Aiswarya recorded higher PFP value (51.67 kg kg$^{-1}$ N applied), which was comparable to Sreyas (51.47 kg kg$^{-1}$ N applied). This enhanced performance is attributed to their greater Root dry weight and root length, which facilitate improved nutrient uptake and utilization efficiency. Research indicates that N-efficient varieties achieve superior grain yield and nitrogen use efficiency ($PFP_N$) (39). Conversely, the lower PFP value observed in KAU Manuvarna (30.55 kg/kg N applied) may be indicative of suboptimal root traits, such as reduced root length or dry weight, limiting N uptake efficiency and productivity. The observed trend aligns with the general understanding that PFP tends to decline as N application rates increase, reflecting diminishing returns in productivity per unit of N applied.

## Harvest Index

The data presented in Table 2 indicate that Harsha (0.34) and Varsha (0.34) recorded higher harvest index values among the SDVs. In contrast, among the MDVs, *Sreyas (0.37) and Aiswarya (0.37)* recorded higher harvest index values among the MDVs. 100 % RDN resulted in a 13.33 % higher harvest index than zero % RDN. Research indicates that the harvest index increases favorably with increasing N levels (40).

No significant interaction effects were observed with respect to harvest index, suggesting that the variety and N level independently influenced the harvest index.

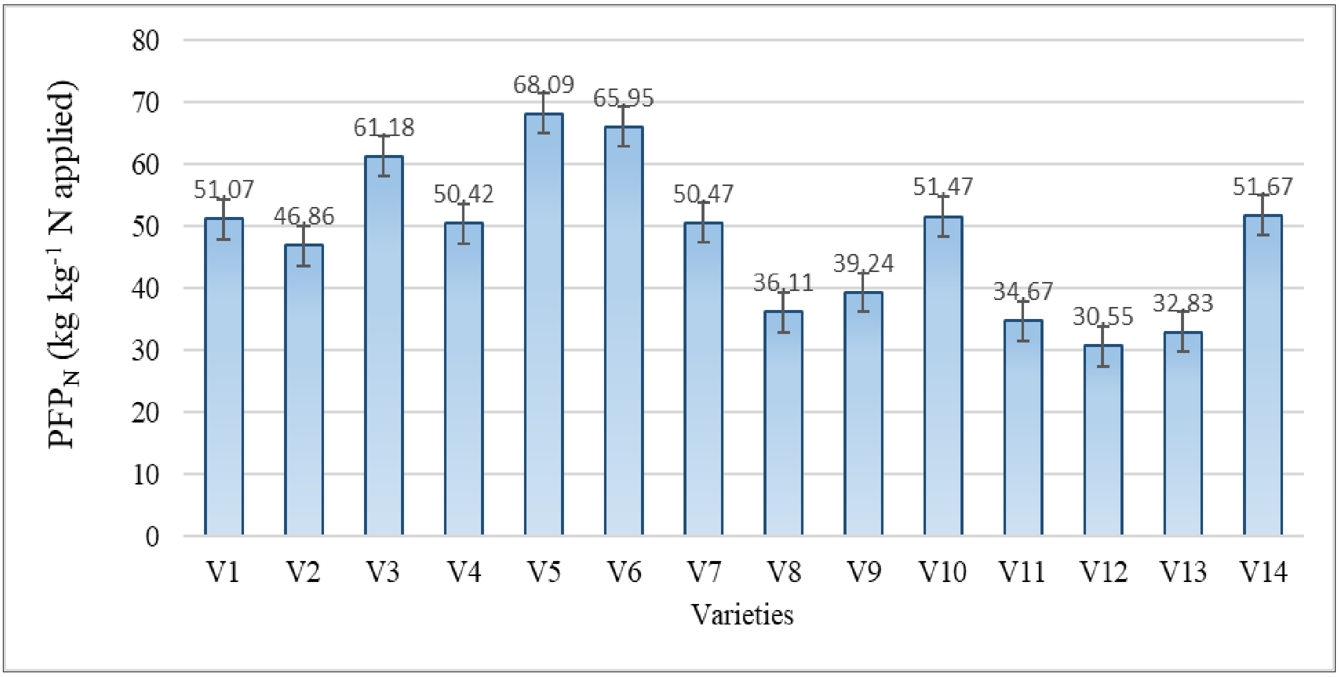


**Fig. 5.** Effect of 100 per cent RDN on partial factor productivity of nitrogen

## Conclusion

Based on the screening of rice varieties under field conditions with varying nitrogen regimes particularly concerning Root dry weight efficiency index, grain yield and partial factor productivity of nitrogen, the short duration varieties, Harsha ($v_5$) and Varsha ($v_6$) and the medium duration varieties Sreyas ($v_{10}$) and Aiswarya ($v_{14}$) were found to outperform others, confirming their potential for efficient nitrogen use. Hence, Harsha (PTB 55), Varsha (PTB 56), Sreyas (MO 22) and Aiswarya (PTB 52) were identified as promising nitrogen use-efficient rice genotypes and selected for detailed field-level evaluation under graded levels of RDN. These traits hold significant potential as foundational criteria for root phenotyping aimed at breeding N-use-efficient rice genotypes. To strengthen these insights, further validation across a broader range of N-use-efficient genotypes is essential, paving the way for the development of high-performing, sustainable rice varieties.

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## Authors' contributions

MJ performed the experiments and wrote the first draft of the manuscript. SP supervised the study, contributed to the research design, arranged resources and carried out manuscript revision and correction. JJ was involved in research design and helped coordinate the availability of resources. NS contributed to the planning of the study and assisted in arranging research materials. AB participated in research design and supported resource management for the study. PG assisted in designing the research framework and in gathering necessary resources. All authors read and approved the final version of the manuscript.

## Compliance with ethical standards

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

**Ethical issues:** None

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