



RESEARCH ARTICLE

# Precision nitrogen management for sustainable rice production: Impacts on nutrient uptake and energy use in Eastern Himalayas

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Received: 29 January 2025; Accepted: 10 April 2026; Available online: Version 1.0: 10 June 2026

**Cite this article:** Ayekpam DD, Anchal D, Jayanta L, Arjun S, Teekam S, Megha K, Kadagonda N, Devika AR . Precision nitrogen management for sustainable rice production: Impacts on nutrient uptake and energy use in Eastern Himalayas. Plant Science Today. 2026;13(sp2):01–12. <https://doi.org/10.14719/pst.13876>

## Abstract

Rice production in the Eastern Himalayas is constrained by declining soil fertility and inefficient nutrient use. This study hypothesised that real-time precision nitrogen management (PNM) using diagnostic tools could maintain high yields while reducing fertiliser inputs compared to conventional methods. A field experiment was conducted in Meghalaya, India, during 2022 to evaluate 8 nitrogen (N) management strategies for rice (var. *Shahsarang-1*). Treatments included control (no-N), the recommended dose of nitrogen (RDN, 80 kg ha<sup>-1</sup>), a soil-test crop response-based application (STCR, 95 kg N ha<sup>-1</sup>) and real-time applications guided by soil plant analysis development (SPAD) meter (thresholds  $\leq 35$  and  $\leq 37$ ) and leaf colour chart (LCC  $< 4$ ). Additionally, treatments combining reduced basal N with nano-urea (NU) foliar sprays were assessed. The highest grain yield and nutrient uptake were recorded in the STCR treatment, which was statistically on par with the SPAD  $\leq 37$  treatment. Notably, the SPAD  $\leq 37$  approach achieved this comparable yield with a lower N application rate than the STCR method. This demonstrates that using a SPAD critical value of  $\leq 37$  can optimise N application, saving fertiliser without compromising crop productivity or net energy returns. While reduced N with NU sprays showed high energy use efficiency, the associated yield penalty makes it unsuitable for farmer adoption. Therefore, SPAD-guided N application is a highly effective and sustainable strategy for enhancing rice production in the Eastern Himalayas.

**Keywords:** leaf colour chart; nano-urea; nutrient-use efficiency; soil plant analysis development; soil-test crop response

## Introduction

Rice (*Oryza sativa* L.) provides the primary caloric intake and ensures food security for over half of the world's population (1, 2). India, as the second-largest producer, plays a pivotal role in the global rice supply chain, with exports valued at approximately US\$ 1.14 billion (3). However, the sustainability of current rice production systems is increasingly under threat. Decades of intensive cultivation, particularly in prime agricultural regions such as the Indo-Gangetic Plains, have resulted in stagnating yields, declining soil health and alarmingly low nitrogen use efficiency (NUE), which often falls below 40 % (4). This inefficiency not only inflates production costs but also contributes significantly to environmental degradation through greenhouse gas emissions and nitrate leaching into water bodies. While much research has focused on the consequences of nutrient over-application in intensive farming systems, a contrasting and equally critical challenge exists in less-developed agricultural frontiers such as the Eastern Himalayas (5). This region, a global biodiversity hotspot, is characterised by traditional, low-input farming systems where farmers cultivate a wide range of indigenous rice cultivars (6). Here, the primary constraint is not nutrient excess but chronic nutrient

deficiency. Regional rice productivity of 2.2 t ha<sup>-1</sup> significantly lags the national average of 2.8 t ha<sup>-1</sup> (7, 8), largely due to inadequate nutrient replenishment in soils inherently prone to acidity, erosion and high phosphorus (P) fixation, compounded by heavy monsoonal rainfall that exacerbates nitrogen (N) losses. Bridging this yield gap is necessary for ensuring regional food security and improving farmers' livelihoods. However, the direct transfer of high-input agricultural models to this ecologically sensitive region is neither feasible nor sustainable. The challenge lies in sustainably intensifying production through enhanced nutrient cycling and efficiency. The principle of 4R nutrient stewardship (right source, right rate, right time and right place), evolved from earlier site-specific nutrient management plan (9), provides a strong scientific foundation for achieving this objective. Among all essential nutrients, N management remains the most critical determinant of rice productivity, governing key physiological processes from chlorophyll synthesis to grain filling (10).

Real-time precision nitrogen management (PNM) tools offer an approach to synchronise N supply with the dynamic demand of the crop. By non-destructively determining leaf chlorophyll content, tools such as the soil plant analysis

development (SPAD) meter and the leaf colour chart (LCC) serve as reliable proxies for plant N status (11–13). Their effectiveness in optimising N inputs and improving NUE has been widely documented. The SPAD-based N scheduling has been shown to reduce fertiliser N use by up to 33 % in rice (14) and improve water-use efficiency (15), while the farmer-friendly LCC has curtailed N application by approximately 23 kg ha<sup>-1</sup> in rice (16) and up to 50 % in maize (17). In addition, emerging innovations such as nano-urea (NU), with reported nutrient delivery efficiencies exceeding 80 %, represent a promising frontier for minimising fertiliser inputs while sustaining crop performance (18). Despite the demonstrated potential of these technologies, a critical research gap persists. Evidence on the performance and adaptability of PNM strategies under the unique low-input, high-rainfall agro-ecosystems of the Eastern Himalayas remains scarce. It is unclear whether these tools can effectively guide N management to close yield gaps without compromising ecological integrity.

Therefore, the present study was designed to test the hypothesis that real-time, sensor-guided N management can achieve yields comparable to or exceeding conventional soil-test-based recommendations, while significantly enhancing N and energy use efficiencies. The primary objective was to evaluate and identify an optimal PNM strategy integrating SPAD, LCC and NU for sustainably improving rice productivity and nutrient uptake among smallholder farmers in the Eastern Himalayan region.

## Materials and Methods

### Experimental site and climatic conditions

The field experiment was conducted during wet season (July to December) of 2022 at the research farm of the ICAR-Research Centre for North Eastern Hill region (ICAR-RC-NEH) in Umiam, Meghalaya, India (25°40' N latitude, 91°55' E longitude and 1010 m above mean sea level). Four weeks old rice seedlings were transplanted on 4 August, 2022 and then harvested on 12 December 2022. The region experiences a sub-tropical humid climate characterised by distinct summer and winter seasons with significant variations in temperature and precipitation. During the

rice growing period, the minimum and maximum temperatures ranged from 9–30 °C. The months of July and August were the hottest and wettest, with mean daily maximum temperatures ranging from 27.8–28.9 °C, with highest relative humidity reaching up to 92.9 % during August (Fig. 1). Then, temperature fell below 15 °C starting from last week of October till December, coinciding with maturity period. Rainfall was maximum during last week of July to mid- August, reaching up to 205.2 mm per week. The experimental soil was inherently acidic (pH 4.75) with clay loam texture (Alfisol), common in the Meghalaya hills, with low organic carbon (2.4 %), available N (237 kg ha<sup>-1</sup>), medium available P (6.5 kg ha<sup>-1</sup>) and medium available potassium (K) (285 kg ha<sup>-1</sup>).

### Experimental design and treatment details

A field experiment was conducted using a randomized complete block design (RCBD) with 8 N management treatments, each replicated 3 times. Rice variety *Shahsarang-1* (RCPL 1-87-8), was selected for the experiment. It is a semi-dwarf, medium duration (145–155 days) plant, primarily adapted to the hill ecosystems of Meghalaya and other high-altitude regions (> 1000 m above mean sea level) of North-East India. The variety is tolerant to low temperature, performs well under low light conditions and has also been reported to exhibit tolerance to iron toxicity. One month old seedlings were transplanted to a well puddled field at a spacing of 20 cm between rows and 15 cm between plants. Five days after transplantation (DAT), gap filling was completed and a standing water of 5 cm was maintained. There was no need for irrigation owing to the well distributed rainfall of the region. The experiment included 8 N management treatments, T<sub>1</sub> as control with no-N application. In T<sub>2</sub>, the recommended dose of nitrogen (RDN) was applied in 3 splits, while T<sub>3</sub> followed a STCR-based N application in 3 splits, STCR equation of the region ( $2.82 \times \text{target yield} - 0.13 \times \text{Soil N}$ ) was used (19), taking target yield as 35 q ha<sup>-1</sup>. Treatments T<sub>4</sub> and T<sub>5</sub> involved applying 30 % of RDN as basal, with additional N supplied when SPAD readings dropped to  $\leq 35$  and  $\leq 37$  respectively. In T<sub>6</sub>, 30 % of RDN was applied as basal and additional N was provided when the LCC reading fell below 4. Treatments T<sub>7</sub> and T<sub>8</sub> involved basal applications of 75 % and 50 % of RDN respectively, supplemented with NU 500 mL acre<sup>-1</sup> through

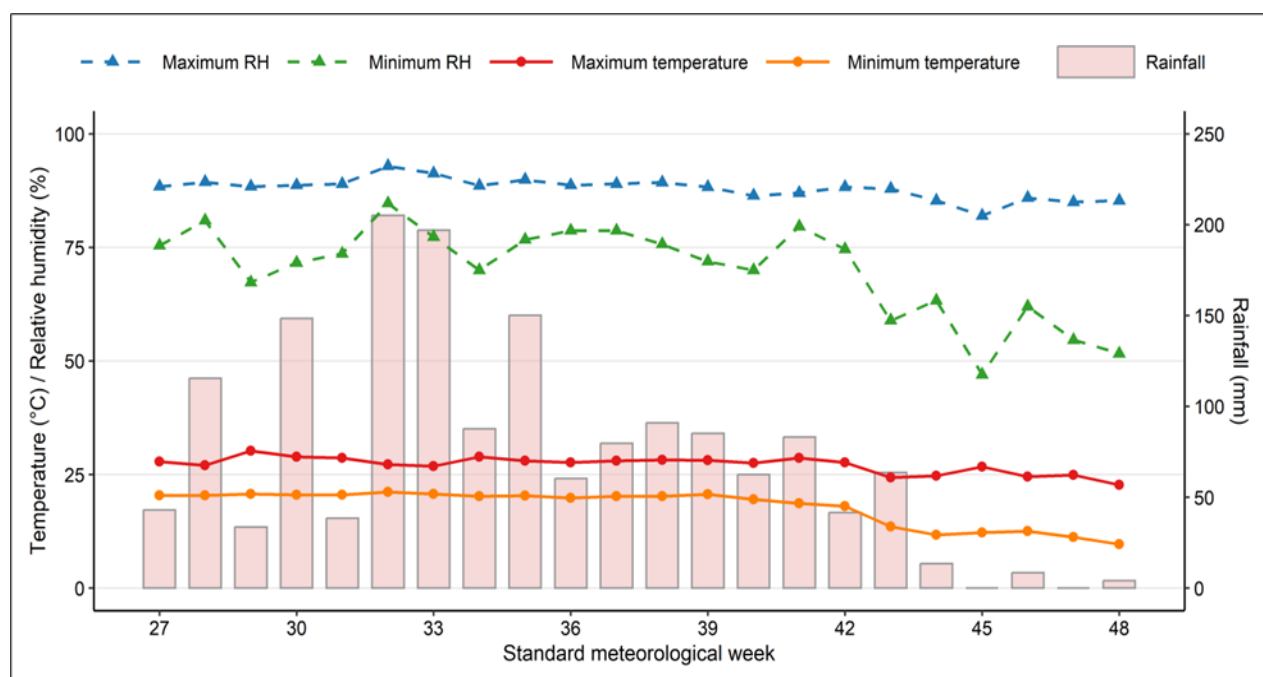


Fig. 1. Weekly meteorological parameters during crop growth period.

2 foliar sprays 30 and 50 DAT.

For RDN, 80 kg ha<sup>-1</sup>N was applied and 95 kg ha<sup>-1</sup>N under soil-test value (STCR based). The P and K were uniformly applied basally at the rate of 60 P<sub>2</sub>O<sub>5</sub> kg ha<sup>-1</sup> and 40 K<sub>2</sub>O kg ha<sup>-1</sup> respectively. Three splits of N in RDN and STCR were applied at basal, 30 and 50 DAT. As for SPAD and LCC, readings were taken at 7 days interval, 20 kg N ha<sup>-1</sup> was applied whenever the reading goes below their respective threshold value. Water was drained out 10 days before harvesting, then as the border and remaining hills were harvested, 2 rows on each side were eliminated. The harvested crop was left in the field for 5 days to allow for proper air-drying, after which the total biomass was measured plot-by-plot.

#### Tillers and dry matter accumulation

The number of tillers from 1 m<sup>2</sup> area was counted 30, 60, 90 DAT and at harvest. Similarly, for dry matter accumulation, uniform plants from 1 m row length were cut from the second row (the sample row) at ground level 30, 60 and 90 DAT. Immediately, the fresh weight of the plant samples were taken using an electronic balance. Then, it was placed in labelled paper bags and dry weight was recorded in gram (g) after being oven-dried at 60 °C.

#### Yield measurement

The matured rice plants from net plots were cut by a sickle and then dried in the sun, after which, the weight (biological yield) was recorded. Then, it underwent threshing and winnowing to get the grain yield, which was noted and expressed in tonnes per hectare. The harvest index was computed with the help of formula given below (20).

$$\text{Harvest index (\%)} = \frac{\text{Economic seed yield (t ha}^{-1}\text{)}}{\text{Biological yield (t ha}^{-1}\text{)}} \times 100 \quad (\text{Eqn. 1})$$

#### Plant nutrient uptake

##### Nitrogen concentration and uptake

At harvest, plant samples were sun-dried and subsequently oven-dried at 60 °C for 24 hr. Oven-dried plant material and air-dried grain samples (12 % moisture) were ground using a Macro-Wiley mill to pass through a 40-mesh sieve. A 0.5 g subsample from each plot was used to determine N concentration using a modified Kjeldahl method (21). Nitrogen uptake (kg ha<sup>-1</sup>) was calculated by multiplying grain yield with the corresponding N concentration (22).

##### Phosphorus and potassium concentration and uptake

Phosphorus concentration in rice grains was estimated using the vanado-molybdophosphoric acid yellow colour method, wherein phosphate reacts with a vanadate-molybdate reagent under acidic conditions to produce a stable yellow complex, which is measured spectrophotometrically (21). Potassium (K) content was determined using a flame photometer, which measures the intensity of light emitted by K ions when introduced into a flame, providing a reliable estimate of K concentration. Nutrient uptake (kg ha<sup>-1</sup>) was computed by multiplying the grain yield with the corresponding P and K concentrations (22).

#### Nutrient harvest index

The nutrient harvest index (NHI) for N, P and K was calculated to assess the proportion of absorbed nutrients translocated to the grain. At harvest, plant samples were separated into grain and straw, oven-dried, weighed and analysed for nutrient concentrations using standard methods. Nutrient uptake in grain and straw was

estimated by multiplying their respective yields with corresponding nutrient concentrations. The NHI was computed using the following formula (23).

Nutrient harvest index (%) =

$$\frac{\text{Nutrient uptake in grain}}{\text{Total nutrient uptake (grain + straw)}} \times 100 \quad (\text{Eqn. 2})$$

#### Estimation of energy dynamics

All inputs used in rice production and the resulting outputs were converted into their respective energy equivalents. The energy equivalents provided in Supplementary Table 1 (24–30) were used to estimate total energy input and output for each input and agronomic operation, expressed in megajoules per hectare (MJ ha<sup>-1</sup>). Energy efficiency indicators were calculated using standard formulae (31, 32).

Energy use efficiency (EUE) = Energy output (MJ ha<sup>-1</sup>)/Energy input (MJ ha<sup>-1</sup>) (Eqn. 3)

Energy productivity (kg MJ<sup>-1</sup>) = Product output (kg ha<sup>-1</sup>)/Energy input (MJ ha<sup>-1</sup>) (Eqn. 4)

Specific energy (MJ kg<sup>-1</sup>) = Energy input (MJ ha<sup>-1</sup>)/Product output (kg ha<sup>-1</sup>) (Eqn. 5)

Net energy (MJ ha<sup>-1</sup>) = Energy output (MJ ha<sup>-1</sup>) – Energy input (MJ ha<sup>-1</sup>) (Eqn. 6)

#### Statistical analysis

All experimental data were initially arranged and screened in Microsoft Excel before statistical analysis. The field experiment was laid out in a RCBD and treatment effects were analysed using analysis of variance (ANOVA) in the R statistical software. Prior to ANOVA, data were tested for normality and homogeneity of variance to ensure compliance with the assumptions of parametric analysis. Treatment means were compared at the 5 % level of significance ( $p \leq 0.05$ ) and mean separation for significant effects was performed using Duncan's multiple range test (DMRT). The ANOVA procedure followed standard statistical methods for agricultural experiments. Graphical visualisation of treatment effects, regression relationships and response trends was carried out using the ggplot2 package in R. Correlation matrices and pairwise relationships among grain yield, growth parameters, biomass accumulation and nutrient uptake were generated using the GGally package, while regression analyses were performed using base R statistical functions. The agricolae package was used for DMRT and related mean comparison procedures.

## Results and Discussion

#### Tiller count

Tiller density in rice was significantly influenced by the nutrient management strategies across all growth stages (30, 60 and 90 DAT) (Table 1). The highest tiller number was observed under SPAD  $\leq 37$  (288 m<sup>-2</sup>) and STCR (286.7 m<sup>-2</sup>) 60 DAT showing superiority of 18.6 % and 17.8 % respectively over the control. These tiller numbers were however, statistically at par with SPAD  $\leq 35$  and LCC  $< 4$ , indicating that chlorophyll-guided N application maintained tillering advantage during the active vegetative phase.

**Table 1.** Effect of different nitrogen management practices on number of tillers at 30-days interval

| Treatment            | Tillers (m <sup>-2</sup> )   |                              |                              |
|----------------------|------------------------------|------------------------------|------------------------------|
|                      | 30 DAT                       | 60 DAT                       | 90 DAT                       |
| Control              | 142.00 ± 6.98 <sup>c</sup>   | 243.33 ± 10.27 <sup>b</sup>  | 235.00 ± 12.25 <sup>b</sup>  |
| RDN                  | 153.67 ± 5.31 <sup>abc</sup> | 261.33 ± 10.08 <sup>ab</sup> | 252.33 ± 10.34 <sup>ab</sup> |
| STCR                 | 163.00 ± 8.52 <sup>a</sup>   | 286.67 ± 17.00 <sup>a</sup>  | 280.00 ± 18.71 <sup>a</sup>  |
| 30 % RDN + SPAD ≤ 35 | 161.00 ± 4.55 <sup>ab</sup>  | 279.67 ± 9.98 <sup>a</sup>   | 270.33 ± 10.87 <sup>a</sup>  |
| 30 % RDN + SPAD ≤ 37 | 164.33 ± 8.58 <sup>a</sup>   | 288.67 ± 11.12 <sup>a</sup>  | 280.00 ± 12.96 <sup>a</sup>  |
| 30 % RDN + LCC < 4   | 161.00 ± 4.90 <sup>ab</sup>  | 279.67 ± 9.81 <sup>a</sup>   | 270.67 ± 11.09 <sup>a</sup>  |
| 75 % RDN + 2 NU      | 153.33 ± 4.92 <sup>abc</sup> | 268.67 ± 8.99 <sup>ab</sup>  | 260.00 ± 10.71 <sup>ab</sup> |
| 50 % RDN + 2 NU      | 148.00 ± 3.74 <sup>bc</sup>  | 262.33 ± 8.81 <sup>ab</sup>  | 254.00 ± 10.42 <sup>ab</sup> |

RDN: recommended dose of N; STCR: soil test crop response; SPAD: soil plant analysis development; LCC: leaf colour chart; NU: nano-urea; similar alphabets within the column signifies non significance at  $p = 0.05$ .

By 90 DAT, tiller number declined across treatments due to natural tiller mortality. However, both SPAD ≤ 37 and STCR sustained the highest counts (280.0 m<sup>-2</sup>), nearly 19 % greater than control. While all PNM treatments outperformed control, the improvement under 50 % RDN+2NU was relatively limited (+8.1 %).

These findings suggest that PNM, particularly SPAD and LCC-based thresholds ensures timely and adequate N availability during critical crop phases. This likely contributed to better tiller initiation and survival, as N plays a central role in promoting cell division and overall vegetative growth. Precision N application, guided by plant-based indicators, helped align N supply with physiological demand, enhancing number of tillers without excessive inputs. Chlorophyll-based N scheduling led to improved crop stand and productivity (33, 34). The result observed here suggests that N scheduling based on PNM tools not only improves tiller initiation but also enhances tiller survival under high-altitude conditions demonstrating that precision N management tools can be reliably extended to hill ecosystem. These findings are broadly consistent with reports from other agro-ecological zones. The SPAD-guided N management maintained significantly higher tiller counts compared to fixed-schedule fertilisation in rice under subtropical eastern India (14), attributing it to better synchronisation of N supply with vegetative demand. Similarly, SPAD 502-meter based N scheduling improved tiller density in wheat by ensuring adequate N availability during tillering period (35). In contrast to intensive irrigated systems of the Indo-Gangetic Plains, where excessive N can suppress effective tiller number through luxury consumption, the present study demonstrates that even modest, need-based N doses under the PNM strategy are sufficient to maximise productive tiller formation in the nutrient-scarce, high-rainfall environment of the Eastern Himalayas. This paradigm shift from input maximisation to demand-based precision is particularly consequential for smallholder hill farmers, as it implies that expensive fertiliser purchases need not be increased; rather, the timing of application, guided by SPAD or LCC

readings, is the critical determinant of productive tillering. In practice, this means farmers can reduce fertiliser costs while maintaining or even improving their crop stand, a direct livelihood benefit.

### Dry matter accumulation (DMA)

Dry matter accumulation (DMA) in rice increased steadily from 30 to 90 DAT, with significant differences among treatments (Table 2). The maximum dry matter was recorded at 90 DAT, where SPAD ≤ 37 recorded the maximum biomass (940.0 g m<sup>-2</sup>), followed by STCR (905.0 g m<sup>-2</sup>) and SPAD ≤ 35 (898.8 g m<sup>-2</sup>), each significantly outperforming control (597.3 g m<sup>-2</sup>) by 36.4 %, 34.0 % and 33.5 % (Table 2). The dry matter produced in 75 % RDN + 2 NU spray was at par with RDN. The dry matter accumulated in PNM treatments and STCR were at par with one and other, while SPAD ≤ 37 and ≤ 35 produces 19.4 % and 14.3 % more dry matter than RDN. The STCR, when well-calibrated, matches the performance of PNM tools. However, the Eastern Himalayas are characterised by considerable spatial and temporal variability in soil and rainfall. Limited access to well-equipped soil testing laboratories in remote hill areas makes STCR challenging for smallholder farmers. In contrast, PNM tools access the actual N status of the plant, making it far more responsive and practical under the dynamic N supply environment of the hills. Real-time N management through SPAD and LCC thresholds consistently enhanced biomass accumulation, indicating a sustained improvement in crop growth rate by improving N availability during critical growth phases. The PNM leads to better chlorophyll retention, canopy expansion and carbon assimilation leading to increased DMA and resource-use efficiency due to the timely N delivery (14, 35). Comparable outcomes have been documented in adjacent agro ecologies. Higher DMA under SPAD-guided N management in direct-seeded rice was reported, attributing the advantage to reduced periods of N deficiency during the grand growth phase (15).

**Table 2.** Effect of different nitrogen management practices on dry matter accumulation of rice at 30-days interval

| Treatment            | Dry matter accumulation (g m <sup>-2</sup> ) |                              |                              |
|----------------------|----------------------------------------------|------------------------------|------------------------------|
|                      | 30 DAT                                       | 60 DAT                       | 90 DAT                       |
| Control              | 140.40 ± 8.37 <sup>e</sup>                   | 298.67 ± 14.38 <sup>d</sup>  | 597.33 ± 28.77 <sup>d</sup>  |
| RDN                  | 211.33 ± 16.36 <sup>bc</sup>                 | 407.23 ± 28.63 <sup>b</sup>  | 786.53 ± 34.26 <sup>b</sup>  |
| STCR                 | 252.00 ± 18.38 <sup>a</sup>                  | 500.33 ± 34.84 <sup>a</sup>  | 905.00 ± 38.94 <sup>a</sup>  |
| 30 % RDN + SPAD ≤ 35 | 238.00 ± 7.96 <sup>ab</sup>                  | 486.85 ± 19.46 <sup>a</sup>  | 898.80 ± 35.92 <sup>a</sup>  |
| 30 % RDN + SPAD ≤ 37 | 250.80 ± 15.44 <sup>a</sup>                  | 517.33 ± 22.23 <sup>a</sup>  | 940.00 ± 37.42 <sup>a</sup>  |
| 30 % RDN + LCC < 4   | 231.20 ± 8.33 <sup>ab</sup>                  | 474.37 ± 18.64 <sup>a</sup>  | 886.32 ± 34.82 <sup>a</sup>  |
| 75 % RDN + 2 NU      | 186.08 ± 7.14 <sup>cd</sup>                  | 381.87 ± 14.39 <sup>bc</sup> | 763.73 ± 28.78 <sup>bc</sup> |
| 50 % RDN + 2 NU      | 163.59 ± 4.98 <sup>de</sup>                  | 348.50 ± 13.21 <sup>c</sup>  | 697.00 ± 26.42 <sup>c</sup>  |

RDN: recommended dose of N; STCR: soil test crop response; SPAD: soil plant analysis development; LCC: leaf colour chart; NU: nano-urea; similar alphabets within the column signifies non-significance at  $p = 0.05$ .

## Yield

Grain and straw yields were significantly influenced by N management strategies (Fig. 2). The STCR-based treatment recorded the highest grain yield, which was however at par with  $\text{SPAD} \leq 37$  and  $\text{SPAD} \leq 35$ -based N applications. These treatments were superior in grain yield by 12 %, 9 % and 5 % over RDN. The comparatively lower grain yield under RDN likely reflects the inherent limitation of fixed-split N scheduling, which cannot dynamically respond to fluctuations in crop N demand or soil N supply across growth stages. While 75 % RDN + 2 NU spray produces marginally lesser yield than RDN, they were statistically at par with each other. These treatments also recorded comparable straw and biological yields, suggesting a balanced partitioning of assimilates. In contrast, the control treatment resulted in a sharp decline in yield, with 28 %, 25.4 % and 20.9 % reduction in grain yield compared to RDN and 75 % RDN+2 NU and 50 % RDN + 2 NU spray highlighting the critical role of adequate N supply in yield realisation (Fig. 2). Straw yield in STCR,  $\text{SPAD} \leq 37$ ,  $\text{SPAD} \leq 35$  and LCC was increased by 12.2 %, 5.02 %, 2.6 % and 6.1 % over RDN. Maximal superiority was also recorded in STCR regarding biological yield (12.1 % > RDN) due to its heavy dose of N applied. The STCR approach grounded in static soil test values and predefined yield targets resulted in relatively higher fertiliser application to achieve the desired yield. The PNM treatments had lesser increment in biological yield with utmost value in  $\text{SPAD} \leq 37$  (7 % > RDN), however, they were comparable with one and other. Real-time N application strategies (SPAD and LCC thresholds) performed on par with STCR despite applying lower total N, reflecting improved synchrony between crop demand and nutrient supply. The performance of crops under PNM largely stems from increased agronomic and recovery efficiencies, achieved through real-time, crop-responsive N management tools, which enable N application to be precisely matched with the crop's actual demand (13). The harvest index (HI) in 50 % RDN + 2 NU and control was 6.7 % and 10.2 % lesser than RDN. The HI in PNM treatments were at par with RDN even though lesser N was applied. The dynamic equilibrium in PNM minimised periods of N deficiency, maintaining photosynthetic efficiency and source-sink

balance during the critical reproductive stages. Timely and demand-based N application enhances yield potential through sustained dry matter production and translocation (1, 36). In the fragile agro-ecosystems of the Eastern Himalayas, PNM, through need-based nutrient application, effectively addresses spatial and temporal variability in soil and crop nutrient demand, thereby enhancing crop yield. Treatments involving NU (75 % and 50 % RDN + 2 NU) showed reduced grain yields compared to RDN, though 75 % RDN + 2 NU remained statistically comparable, indicating its potential to partially offset lower basal N application. Nano-urea, while economically advantageous, is more effective as a supplement rather than a complete replacement for conventional N sources (37). The yield advantage of  $\text{SPAD} \leq 37$  over the fixed-schedule RDN achieved with lower total N input is arguably the most paradigm-shifting finding of this study. Conventional rice agronomy in the Eastern Himalayas has historically relied on blanket fertiliser application (i.e., RDN) derived from regional averages, which cannot account for the high spatio-temporal variability in rainfall, soil N mineralisation and crop growth rate characteristic of the Eastern Himalayan foothills. The present data empirically demonstrate that a crop-responsive, real-time strategy  $\text{SPAD} \text{ threshold} \leq 37$  can displace the soil-test approach as the yield-optimal strategy while simultaneously saving fertiliser. This represents a fundamental shift from input-driven to crop-demand-driven N management.

These findings resonate with and extend the seminal work of who demonstrated in irrigated lowland rice in China that real-time N management based on crop N status monitoring increased NUE without penalising yield (36). Similarly, a SPAD critical value of 37–38 was optimal for maximising both yield and NUE in rice under eastern India conditions the same threshold that proved most effective in the present study, suggesting a robustness of this critical value across diverse rice production environments, including the hill ecosystem (14). Site-specific nutrient management (SSNM) approaches closely matching crop N demand consistently outperformed blanket recommendations in wheat, a principle that our result now extend to rice under high-altitude, rain-fed conditions (38).

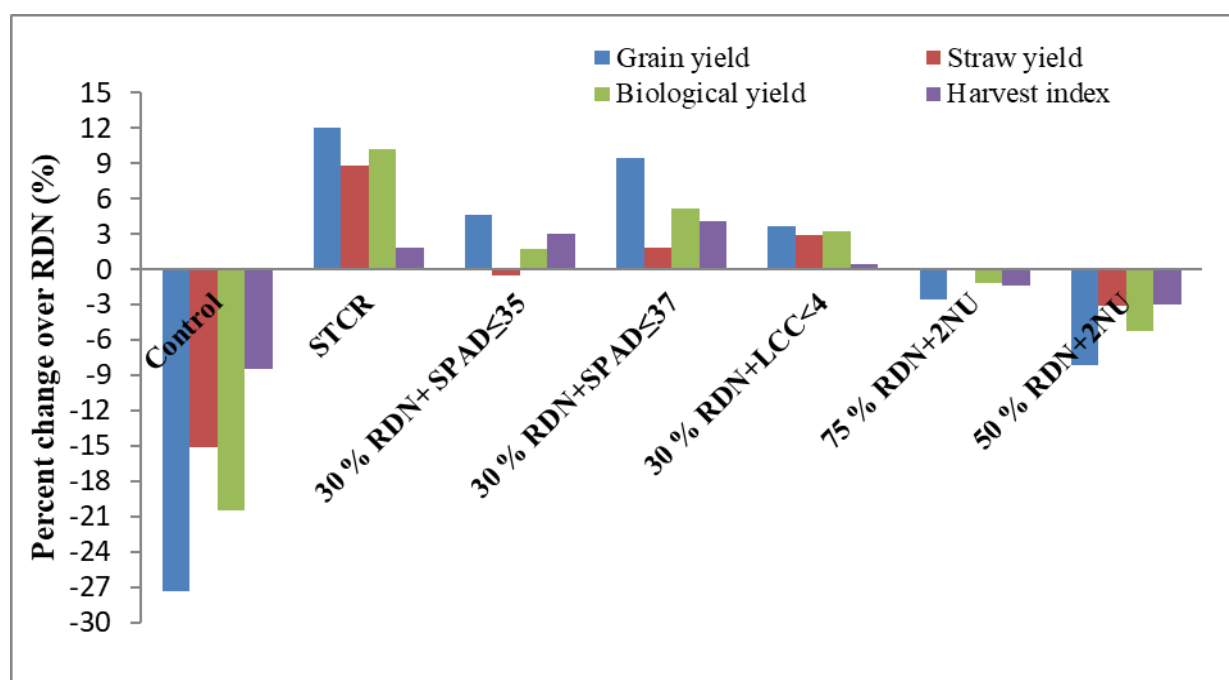


**Fig. 2.** Effect of different nitrogen management practices on yield and harvest index of rice.

## Nutrient uptake

The data pertaining to N content in plant and its uptake in straw are provided in Supplementary Table 2. The highest total N uptake was recorded under SPAD  $\leq 37$ , followed closely by STCR, SPAD  $\leq 35$ , LCC  $< 4$ , all of which remained statistically comparable to STCR (Fig. 3). The total N uptake in STCR, SPAD  $\leq 37$ , were 18.9 %, 19.2 % more than RDN. The total N uptake in RDN was however at par with 75 % RDN + 2NU and 6 % greater than 50 % RDN + 2NU. The 50 % RDN + 2NU and control treatments showed markedly lower N uptake compared to other treatments, indicating that substantial reductions of 50 % RDN in basal N, even when supplemented with NU, were insufficient to meet crop N demand. The enhanced N uptake under STCR and PNM treatments can be attributed to better synchrony between N availability and crop demand, enabled by real-time application guided by chlorophyll-based tools. Improved N-use efficiency in these treatments is likely the result of split applications timed to match key growth stages (39). Further, PNM optimises uptake by reducing losses and ensuring availability during peak demand (40). The SSNM, strategies have been shown to enhance plant N accumulation by minimising mismatches between supply and physiological need (38).

The values in relation to plant P and K content and its uptake in straw are given in Supplementary Table 3 and 4. The grain-P and grain-K uptake in PNM treatments were statistically comparable with STCR and superior over control and 50 % RDN + 2NU (Fig. 3). The PNM approaches: SPAD  $\leq 35$ , LCC  $< 4$  and other N management such as RDN, 75 % RDN + 2NU showed intermediate values and were statistically similar among themselves. The total P

-uptake in STCR was superior by 22.7 %, 8.5 % and 22.3 %, while SPAD  $\leq 37$  by 26.7 %, 12.0 % and 26.3 % over RDN, 75 % RDN + 2NU and 50 % RDN + 2NU (Fig. 3). Similarly, total K uptake in PNM treatments and STCR was superior to 50 % RDN + 2NU and control (Fig. 3). It reflects the importance of balanced nutrient supply not only in quantity, as emphasised in STCR, but also in timing and synchrony as achieved through PNM. The improved uptake under these treatments enhanced root activity, nutrient mobility and efficient use of available soil and applied nutrients.

Notably, the use of NU at 75 % RDN sustained comparable NPK uptake to RDN, suggesting its potential as a supplemental source when used judiciously. The immediate absorption and reduced fixation of nano-scale nutrients may contribute to improved efficiency (30). However, further reduction to 50 % RDN + 2NU led to significant declines in all three nutrient uptake parameters, confirming that excessive reliance on NU, without adequate basal supply, limits its effectiveness in meeting the crop's nutrient demand. The superior N, P and K uptake under PNM treatments, despite applying lower absolute N doses than STCR, strongly supports the premise that synchrony between N supply and crop demand is more important than the total quantity of N applied. This principle, established in irrigated rice systems (30, 38) was demonstrated to hold equally in the low-input, high-rainfall conditions of the Eastern Himalayas, an important scientific contribution of the present study. Split N applications timed to crop demand significantly improved N uptake efficiency in a rice-wheat system under variable N management strategies (39); the present study extends this principle to hill rice using real-time plant sensors rather than calendar-based splits.

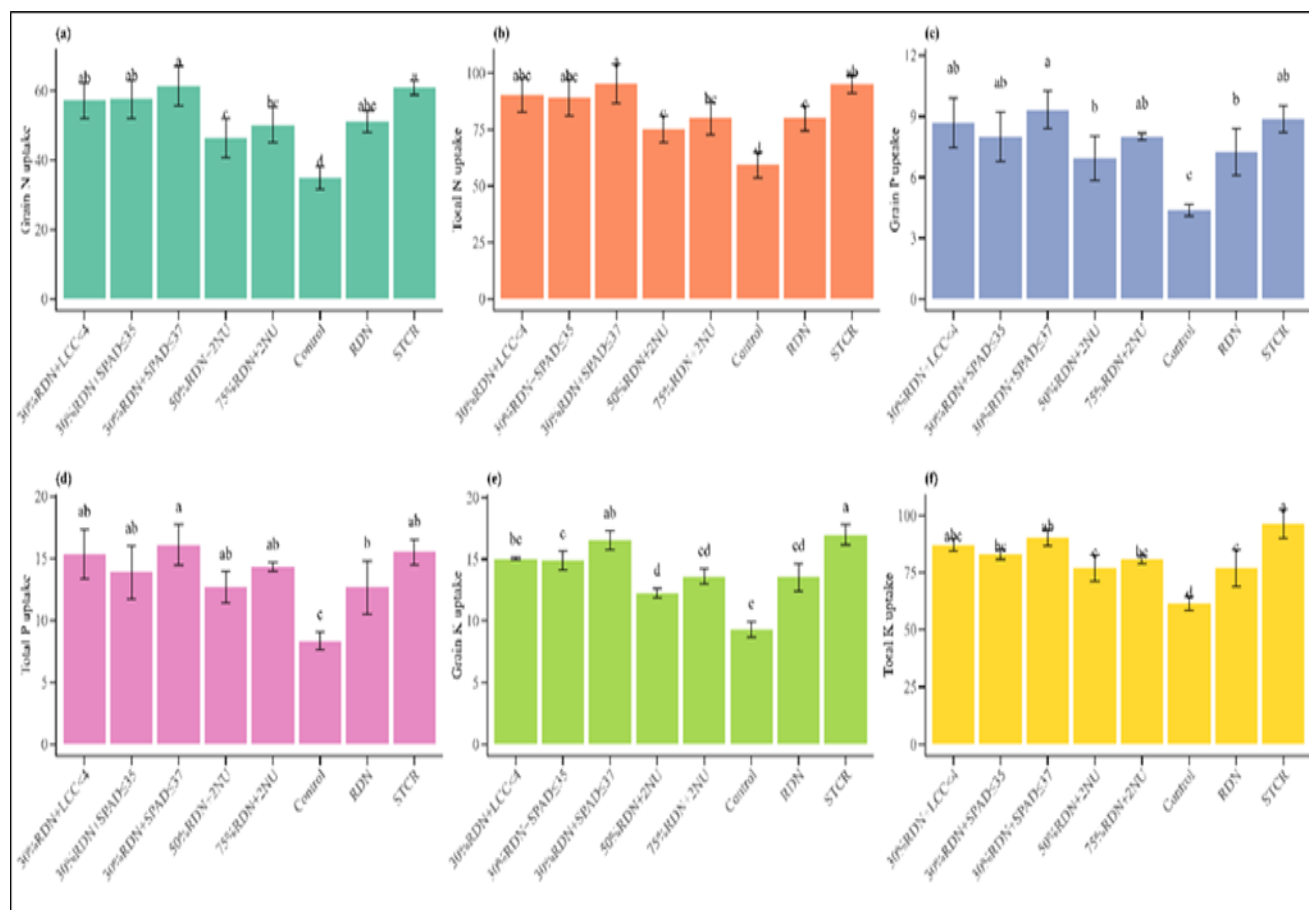


**Fig. 3.** Effect of different nitrogen management practices on grain N; a: total N; b: grain P; c: total P; d: grain K; e: total K uptake; f: of rice. Similar alphabets within the column signifies non-significance at  $p = 0.05$ .

## Correlation and regression analysis

### Correlation analysis

Grain yield showed a strong positive association with tiller numbers, with correlation coefficients of  $r = 0.703$ ,  $0.758$  and  $0.742$  at 30, 60 and 90 DAT respectively (Fig. 4). The maximum association at mid-tillering points out the critical role of N availability during this stage, which is addressed through SPAD and LCC-guided precision N management. The DMA showed an even stronger relationship with grain yield, with correlations increasing from  $r = 0.820$  (30 DAT) to  $0.837$  (60 DAT) and  $0.862$  (90 DAT), indicating that dry matter production at later stages is a key factor of yield. Among all the correlations, grain yield was most strongly correlated with N uptake, grain N uptake ( $r = 0.972$ ) and total N uptake ( $r = 0.961$ ), suggesting that yield enhancement under PNM was driven primarily by improved N acquisition and utilisation efficiency. However, increase in grain yield with improved crop N uptake works up to an optimum SPAD threshold, beyond which further N addition did not result in yield gains (14). Strong inter-relationships among tiller density, DMA and nutrient uptake further highlight the integrated nature of crop growth and nutrient dynamics. Tiller density at 60 and 90 DAT showed strong associations with DMA and nutrient uptake, while DMA at later stages revealed near-perfect correlations with total N uptake ( $r = 0.981$  at 60 DAT;  $r = 0.901$  at 90 DAT) (Fig. 4).

### Regression analysis

Grain yield showed a significant linear response to tiller density at 90 DAT, interpreting 55.1 % of yield variability ( $R^2 = 0.551$ ;  $p < 0.001$ ) (Fig. 5). Dry matter accumulation at 90 DAT exhibited a strong curvilinear relationship with grain yield ( $R^2 = 0.795$ ;  $p = 0.007$ ). Overall, grain yield was most strongly associated with N uptake. Grain N uptake showed a highly significant quadratic relationship with yield, explaining 96.2 % of yield variation ( $R^2 = 0.962$ ;  $p < 0.001$ ), while total N uptake also exhibited a strong curvilinear response ( $R^2 = 0.948$ ;  $p < 0.001$ ), indicating yield saturation beyond optimum N uptake. Significant positive linear relationships were also observed between grain yield and grain P uptake ( $R^2 = 0.829$ ;  $p < 0.001$ ) and total P uptake ( $R^2 = 0.770$ ;  $p < 0.001$ ) (Fig. 5), highlighting synergistic improvements in P acquisition under precision N management.

Overall, correlation & regression analysis indicated that yield and dry matter enhancement under PNM are driven primarily by optimised nutrient uptake as SPAD values are positively correlated with plant N content (14, 27), highlighting the effectiveness of SPAD-guided N strategies in achieving near-optimal nutrient use.

The quadratic relationship between grain N uptake and grain yield ( $R^2 = 0.962$ ) is particularly instructive from a

management standpoint: it mathematically confirms the existence of an N saturation threshold in hill rice, beyond which additional N uptake yields diminishing returns in grain production. This corroborates the SPAD-threshold concept by applying N only when crop chlorophyll falls below  $\leq 37$ , farmers effectively keep the crop operating at the steep ascending portion of this quadratic curve, avoiding both N deficiency and luxury N consumption. This is precisely the mechanistic explanation for why  $SPAD \leq 37$  matched STCR (which applied 15 kg more N  $ha^{-1}$ ) in grain yield while improving NUE. A similar saturation pattern in rice-wheat systems in eastern India using SPAD-based N management, providing independent corroboration of this curvilinear N-yield relationship across contrasting environments was reported (14).

### Nutrient harvest index of nitrogen, phosphorous and potassium

Nutrient harvest indices for nitrogen (NHI), phosphorus (PHI) and potassium (KHI) varied significantly among treatments, reflecting differences in nutrient partitioning efficiency (Table 3). The highest NHI was observed under  $SPAD \leq 35$  (64.51 %),  $SPAD \leq 37$  (64.38 %), RDN (64.09 %) and STCR (64.03 %), all of which were on par with one and other. Similarly,  $SPAD \leq 37$  also recorded the highest PHI (58.26 %) and KHI (18.26 %), followed closely by  $SPAD \leq 35$  and STCR, with no significant differences among these treatments. In contrast, control ( $< 8.0\%$ ,  $< 7.9\%$ ,  $< 8.6\%$ ,  $< 8.5\%$  and  $< 6.9\%$ ) and 50 % RDN + 2 NU ( $< 4.4\%$ ,  $< 4.3\%$ ,  $< 5.0\%$ ,  $< 4.8\%$  and  $< 3.2\%$ ) consistently showed the lower N harvest indices compared to RDN, STCR,  $SPAD \leq 35$ ,  $\leq 37$  and LCC  $< 4$ , indicating poor translocation of absorbed nutrients to grain (Table 3). Similarly, PNM treatments showed marginally higher P and K harvest index (HI) than STCR and RDN, though, they were statistically at par. The 50 % RDN + 2 NU spray lagged as compared to other N applied treatments. The superior NHI, PHI and KHI under SPAD and LCC strategies can be attributed to optimised N availability during key growth stages, improving plant vigour and enhanced primary nutrient uptake leading to efficient remobilisation into grain. The SPAD-based tools, by quantifying chlorophyll content, enable more precise detection of N need than LCC, which is based on visual cues. This marginal precision advantage likely explains the slightly higher harvest indices observed under SPAD-based treatments. In RDN and STCR treatments, higher total N application improved uptake, but the partitioning efficiency was matched by precision treatments applying less total N. Synchronising nutrient supply with physiological demand enhances nutrient-use efficiency and partitioning (31, 41). The 75 % RDN + 2 NU treatment also maintained comparable NHI values to PNM, suggesting that NU can supplement reduced basal N. However, reducing N further to 50 % RDN + 2 NU significantly lowered all 3 HI, indicating insufficient nutrient availability.

**Table 3.** Effect of different nitrogen management practices on nutrient harvest index (NPK) of rice

| Treatment                 | Nutrient harvest index (%)     |                                |                                |
|---------------------------|--------------------------------|--------------------------------|--------------------------------|
|                           | Nitrogen                       | Phosphorus                     | Potassium                      |
| Control                   | 58.91 $\pm$ 1.39 <sup>c</sup>  | 52.73 $\pm$ 1.28 <sup>c</sup>  | 15.16 $\pm$ 0.66 <sup>c</sup>  |
| RDN                       | 64.09 $\pm$ 0.73 <sup>a</sup>  | 57.24 $\pm$ 0.78 <sup>ab</sup> | 17.65 $\pm$ 0.46 <sup>ab</sup> |
| STCR                      | 64.03 $\pm$ 0.69 <sup>a</sup>  | 57.17 $\pm$ 0.74 <sup>ab</sup> | 17.61 $\pm$ 0.44 <sup>ab</sup> |
| 30 % RDN + SPAD $\leq$ 35 | 64.51 $\pm$ 0.76 <sup>a</sup>  | 57.69 $\pm$ 0.81 <sup>a</sup>  | 17.91 $\pm$ 0.49 <sup>a</sup>  |
| 30 % RDN + SPAD $\leq$ 37 | 64.38 $\pm$ 0.29 <sup>a</sup>  | 58.26 $\pm$ 0.44 <sup>a</sup>  | 18.26 $\pm$ 0.27 <sup>a</sup>  |
| 30 % RDN + LCC $<$ 4      | 63.33 $\pm$ 0.91 <sup>ab</sup> | 56.65 $\pm$ 0.97 <sup>ab</sup> | 17.30 $\pm$ 0.56 <sup>ab</sup> |
| 75 % RDN + 2 NU           | 62.52 $\pm$ 1.12 <sup>ab</sup> | 55.84 $\pm$ 0.82 <sup>ab</sup> | 16.83 $\pm$ 0.46 <sup>ab</sup> |
| 50 % RDN + 2 NU           | 61.27 $\pm$ 2.97 <sup>bc</sup> | 54.30 $\pm$ 3.12 <sup>bc</sup> | 16.06 $\pm$ 1.75 <sup>bc</sup> |

RDN: recommended dose of N; STCR: soil test crop response; SPAD: soil plant analysis development; LCC: leaf colour chart; NU: nano-urea; Similar alphabets within the column signifies non-significance at  $p = 0.05$ .

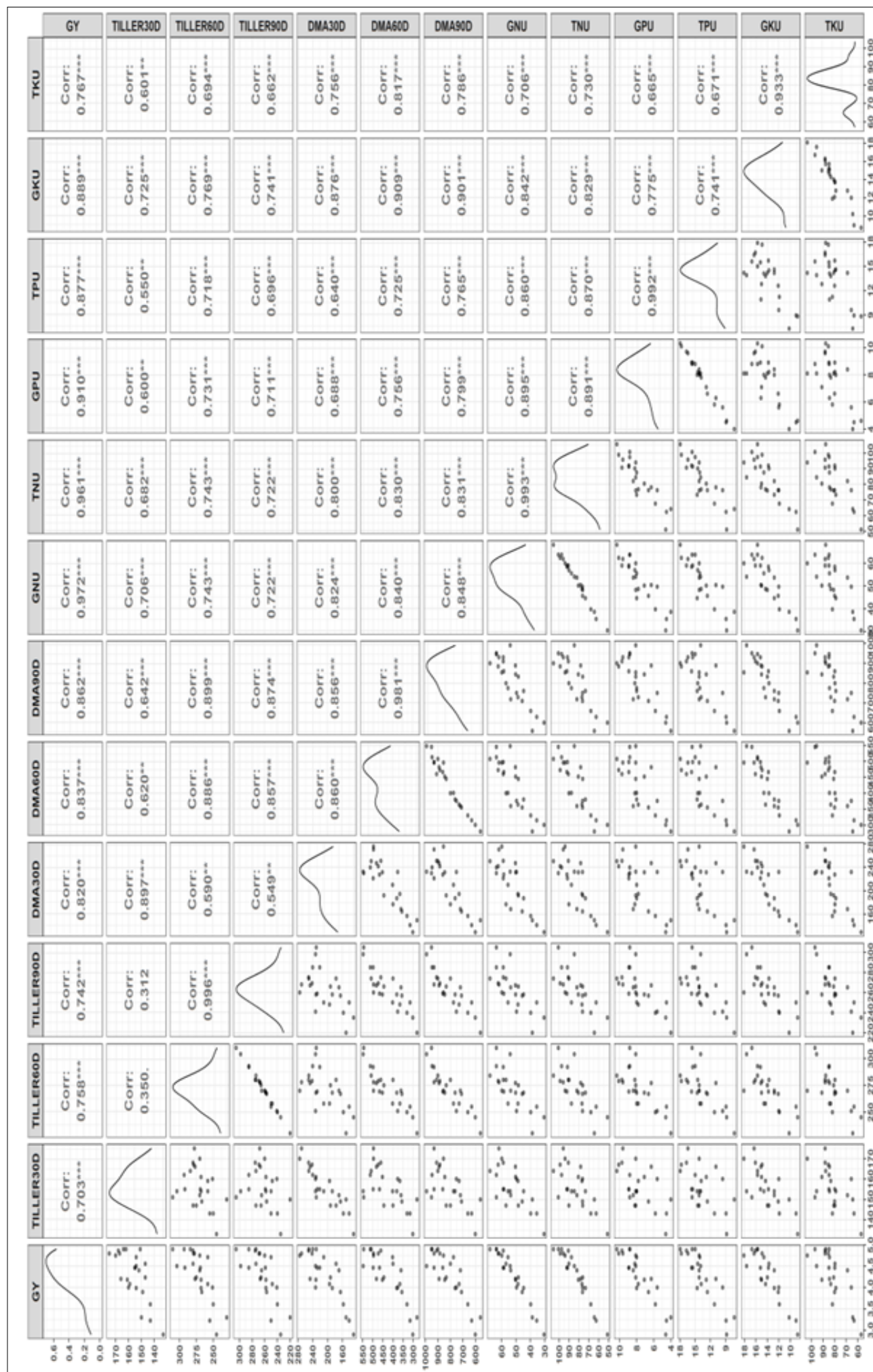


**Fig. 4.** Correlation matrix between grain yield (GY), tiller and dry matter accumulation (DMA) - 30 day interval, grain N, P and K uptake (GNU, GPU, GKU) and total nitrogen (N), phosphorous (P) and potassium (K) uptake (TNU, TPU, TKU). Significance level: \*\*\*0.001, \*\*0.01, \*0.05.

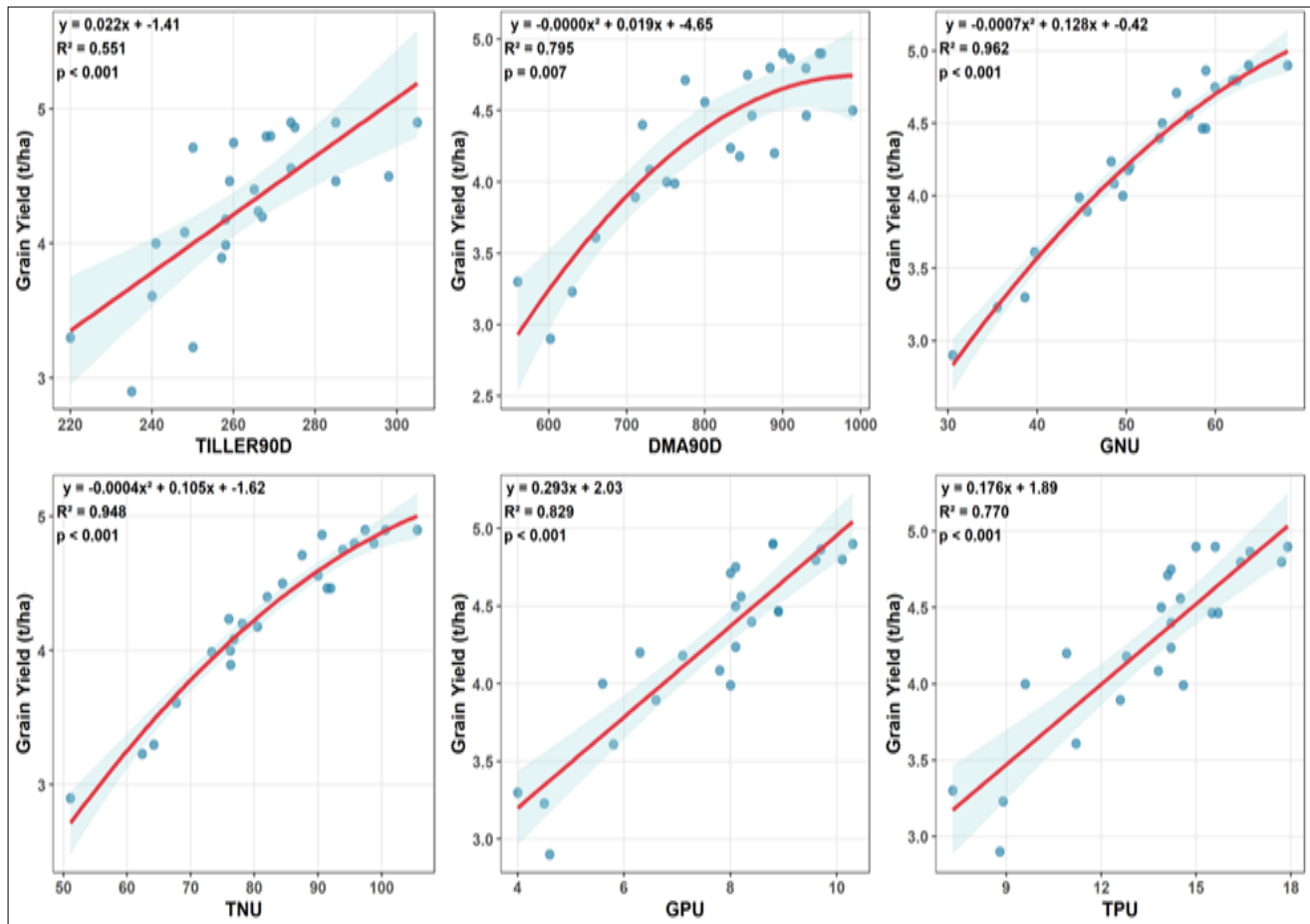


**Fig. 5.** Regression analysis showing the relationship of grain yield with tillers, dry matter accumulation (DMA)-90 DAT, grain nitrogen (N), phosphorous (P) uptake (GNU, GPU) and total nitrogen (N), phosphorous (P) uptake (TNU, TPU).

## Energy dynamics

### Energy input and output

A high NHI indicates efficient remobilisation of stored N from vegetative tissues to the grain during the reproductive phase, which is the hallmark of a healthy source-sink relationship. The NHI values ranges from 58–65 % for well-managed lowland rice in North-East India under organic-based nutrient management (23), a benchmark that our PNM treatments equalled and, in the case of SPAD  $\leq 35$ , marginally exceeded. The fact that PNM-treated crops achieved these NHI values while receiving less N than STCR-treated crops demonstrate superior internal N cycling efficiency, which is a prerequisite for building sustainable production systems in ecologically sensitive hill areas where N loss to leaching and volatilisation is high due to heavy monsoon rainfall.

The energy dynamics in the different N management strategies are shown in Table 4. The highest energy consumption was observed in the STCR treatment (9255 MJ ha<sup>-1</sup>) and RDN (8346 MJ ha<sup>-1</sup>), 25.4 % and 13.1 % more energy consumed than PNM treatments, which was due to high upfront N application in the former treatments. The lowest inputs were recorded in 50 % RDN + 2 NU (5927 MJ ha<sup>-1</sup>) and control (3498 MJ ha<sup>-1</sup>). While 75 % RDN + 2 NU spray uses 14.4 % lesser energy input as compared to RDN, however, their energy output was statistically at par with each other. This initial finding highlights that PNM approaches can reduce the energy footprint of cultivation. Corresponding with grain yield trends, energy output was maximised under the STCR treatment (146015 MJ ha<sup>-1</sup>), which was however, statistically comparable with SPAD  $\leq 37$  (139627 MJ ha<sup>-1</sup>) and LCC < 4 (136703

**Table 4.** Effect of different nitrogen management practices on energy dynamics of rice

| Treatment                 | EI (MJ ha <sup>-1</sup> ) | EO (MJ ha <sup>-1</sup> )   | NEO (MJ ha <sup>-1</sup> )  | EUE                     | SE (MJ kg <sup>-1</sup> ) | EPv (kg MJ <sup>-1</sup> ) |
|---------------------------|---------------------------|-----------------------------|-----------------------------|-------------------------|---------------------------|----------------------------|
| Control                   | 3498                      | 104579±6475 <sup>c</sup>    | 101081±6475 <sup>c</sup>    | 29.9 ± 1.8 <sup>a</sup> | 1.12 ± 0.06 <sup>c</sup>  | 0.90 ± 0.05 <sup>a</sup>   |
| RDN                       | 8346                      | 130189 ± 10591 <sup>b</sup> | 121843 ± 10591 <sup>b</sup> | 15.6 ± 1.2 <sup>d</sup> | 1.94 ± 0.13 <sup>a</sup>  | 0.52 ± 0.04 <sup>d</sup>   |
| STCR                      | 9255                      | 146015 ± 2926 <sup>a</sup>  | 136760 ± 2926 <sup>a</sup>  | 15.7 ± 0.3 <sup>d</sup> | 1.91 ± 0.03 <sup>a</sup>  | 0.52 ± 0.01 <sup>d</sup>   |
| 30 % RDN + SPAD $\leq 35$ | 7377                      | 134915 ± 7368 <sup>ab</sup> | 127538 ± 7368 <sup>ab</sup> | 18.2 ± 1.0 <sup>c</sup> | 1.64 ± 0.10 <sup>b</sup>  | 0.61 ± 0.04 <sup>bc</sup>  |
| 30 % RDN + SPAD $\leq 37$ | 7377                      | 139627 ± 5817 <sup>ab</sup> | 132250 ± 5817 <sup>ab</sup> | 18.9 ± 0.8 <sup>c</sup> | 1.56 ± 0.06 <sup>b</sup>  | 0.64 ± 0.02 <sup>bc</sup>  |
| 30 % RDN + LCC < 4        | 7377                      | 136703 ± 6410 <sup>ab</sup> | 129326 ± 6410 <sup>ab</sup> | 18.5 ± 0.8 <sup>c</sup> | 1.65 ± 0.09 <sup>b</sup>  | 0.61 ± 0.03 <sup>bc</sup>  |
| 75 % RDN + 2 NU           | 7139                      | 130697 ± 6485 <sup>b</sup>  | 123558 ± 6485 <sup>a</sup>  | 18.3 ± 0.9 <sup>c</sup> | 1.70 ± 0.10 <sup>b</sup>  | 0.59 ± 0.03 <sup>cd</sup>  |
| 50 % RDN + 2 NU           | 5927                      | 127210 ± 2887 <sup>b</sup>  | 121283 ± 2887 <sup>b</sup>  | 21.4 ± 0.5 <sup>b</sup> | 1.50 ± 0.12 <sup>b</sup>  | 0.67 ± 0.06 <sup>b</sup>   |

EI: energy input; EO: energy output; NEO: net energy output; EUE: energy use efficiency; SE: specific energy; EPv: energy productivity; RDN: recommended dose of N; STCR: soil test crop response; SPAD: soil plant analysis development; LCC: leaf colour chart; NU: nano-urea.

MJ ha<sup>-1</sup>) (Table 4). This demonstrates that real-time, need-based N application can sustain high productivity levels, nearly matching the output of more input-intensive systems. Consequently, the net energy return, was highest not only in STCR (136760 MJ ha<sup>-1</sup>) but also impressively high in other PNM treatments with an increment of 8.5 % in SPAD  $\leq$  37 than RDN. This suggests that the energetic advantage of PNM lies in its ability to maintain high net energy gains by optimising the balance between inputs and outputs. The substantially lower energy input under PNM treatments primarily because N fertiliser constitutes the dominant energy-intensive input in rice production has broad implications for the sustainability discourse in hill agriculture. The SPAD-guided direct-seeded rice in the Indo-Gangetic Plains achieved a superior energy use efficiency compared to fixed-schedule fertilisation (15), a finding that the present study corroborates under the starkly different conditions of the Eastern Himalayas. The near-equivalent energy output between SPAD  $\leq$  37 and STCR at markedly lower energy input captures the essence of the efficiency-sustainability trade-off: both strategies deliver similar yields, but the energetic cost of production differs substantially, with direct consequences for farm profitability and environmental footprint.

#### Energy use efficiency (EUE)

The control treatment exhibited the highest energy use efficiency (EUE) (29.9), primarily due to minimal energy inputs rather than productive efficiency and is therefore impractical due to associated yield penalty. The PNM treatments viz. SPAD  $\leq$  37, LCC  $<$  4, SPAD  $\leq$  35 recorded significantly higher EUE; 19.9 %, 17.5 % and 15.9 % more efficient than STCR and 21.3 %, 18.8 % and 17.2 % than RDN (Table 4). The treatment under 75 % RDN + 2 NU spray was 17.3 % more energy efficient than 100 % RDN. The STCR and RDN produced high absolute outputs; however, their efficiency in converting energy inputs into biomass was poor. The superior EUE of the PNM treatments indicates that synchronising N supply with crop demand minimises nutrient losses and ensure that a larger fraction of the energy invested is productively converted into grain energy. Optimised nutrient management directly enhances the energy conversion efficiency in cereal cropping systems (15). The ~20 % improvement in EUE of SPAD  $\leq$  37 relative to STCR represents a meaningful advance in sustainable intensification metrics for hill rice. The EUE values in the range of 18–19 for SPAD/LCC treatments compare favourably with those reported for optimised rice management across diverse South Asian environments. EUE values ranging from 15–17 was reported for promising rice cultivars in the Eastern Himalayas under varied nutrient management, while the present study using locally adapted variety *Shahsarang-1* with precision N management achieved values exceeding 18, indicating room for further optimisation through variety and management interaction studies (6).

#### Specific energy (SE) and energy productivity (EP)

The RDN (1.94 MJ kg<sup>-1</sup>) and STCR (1.91 MJ kg<sup>-1</sup>) were the most energy-costly (Table 4), demanding nearly twice the energy per kg of grain as control (1.12 MJ kg<sup>-1</sup>). In stark contrast, the SPAD  $\leq$  37 treatment recorded the lowest SE among all fertilised treatments (Table 4), using 18.3 % and 19.6 % lesser energy than STCR and RDN. While the 75 % RDN + 2 NU spray treatment uses 12.3 % lesser specific energy than RDN. The specific energy of PNM treatments was statistically at par with one and other. This demonstrates superior energy investment efficiency, producing high yields at a significantly lower energetic cost per unit. The EP,

the reciprocal of SE confirms this interpretation, STCR and RDN treatments were the least productive (0.52 kg MJ<sup>-1</sup>), reinforcing that their high yields were achieved through an inefficient, heavy application of energy. Conversely, the SPAD  $\leq$  37 treatment exhibited commendable productivity (0.64 kg MJ<sup>-1</sup>), surpassed only by control and 50 % RDN + 2 NU spray which produced substantially lower yields (Table 4). Moving beyond yield-centric assessments to include efficiency metrics like SE and EP is crucial for developing sustainable agricultural practices (6, 42). Our results empirically support their conclusion, showing that precision tools enable a farming system that is both productive and energetically efficient. The specific energy of 1.56 MJ kg<sup>-1</sup> under SPAD  $\leq$  37 and 1.65 MJ kg<sup>-1</sup> under LCC  $<$  4, compared to 1.91–1.94 MJ kg<sup>-1</sup> under STCR and RDN, indicate that precision N management fundamentally alters the energy economics of rice production in the Eastern Himalayas. Site-specific fertiliser management in South Asian cereal systems is prerequisite to improve energy productivity (42). The present study provides field-level evidence validating this proposition specifically for the Eastern Himalayan hill rice system, which has been largely overlooked in the precision agriculture literature. The energy productivity of 0.64 kg MJ<sup>-1</sup> under SPAD  $\leq$  37 implies that for every megajoule of energy invested (in all inputs combined), the farmer recovers 0.64 kg of marketable grain compared to only 0.52 kg under the conventional STCR approach. This 23 % improvement in EP under SPAD guidance without yield loss is compelling evidence that SPAD-based N management is the optimal strategy for energy-efficient, commercially viable rice farming in the Eastern Himalayan region.

### Conclusion

Precision nitrogen (N) management based on soil plant analysis development (SPAD) thresholds ( $\leq$  37 and  $\leq$  35) and an leaf colour chart (LCC) critical value of  $<$  4 offers a robust strategy for optimising rice productivity in the Eastern Himalayan region. The SPAD threshold 37 showed marginally better response than 35 and LCC with threshold 4. The precision nitrogen management (PNM) approach not only boosts productivity but also promotes sustainable farming practices by reducing excessive N use, saving up to 30 % N with respect to soil-test crop response (STCR) and 18.3 % and 19.6 % energy input as compared to STCR and recommended dose of nitrogen (RDN), without compromising the yield. As for nano urea (NU), 2 sprays can be used as a supplement to 75 % RDN, but cutting it off to 50 % RDN caused yield penalty, which showed that the claim of replacement of urea with NU as a whole is questionable. As climate variability continues to challenge traditional rice farming, integrating SPAD and LCC-based N management offers a practical and scalable solution for farmers seeking to improve efficiency and profitability. To confirm the consistency and wider relevance of these findings, multi-year studies in a variety of environmental circumstances are needed. However, the current work offers a helpful starting point for further long-term research on precision N management in rice systems in the Eastern Himalayan region of India.

### Acknowledgements

The authors acknowledge the ICAR Research Complex for the North Eastern Hill region, Meghalaya, for providing the necessary

facilities to conduct this research. The authors also express sincere thanks to the field and laboratory staff for their assistance during experimentation and analysis. Finally, the corresponding author gratefully acknowledges ICAR-Indian Agricultural Research Institute for providing financial support.

## Authors' contributions

ADD wrote the first manuscript. AD designed the experiment and treatments. ADD collected data from field, analysed samples and recorded SPAD and LCC readings under the guidance of AD and JL. AS helped in preparing figures and tables. AD and AS gave suggestions regarding the content of the paper. ADD, TS, MK, KN and DAR read the manuscript to check grammatical, spelling mistakes and counter-checked the references. 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.

**Ethical issues:** None

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Google Gemini in order to create graphical abstract. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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