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Precision nitrogen management for improved root architecture, micronutrient acquisition, and rice productivity in the north-eastern hill region of India

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Abstract

Agriculture is the primary source of livelihood in the North-Eastern Hill (NEH) region of India, where rice, the staple food crop, holds paramount importance for farmers. However, declining productivity and low nutrient use efficiency have emerged as major constraints in the region. Most farmers continue to follow blanket fertilizer application practices, particularly for nitrogen (N), resulting in uneven and inefficient nutrient use. Precision nitrogen management (PNM), through the use of N-stress sensing tools, offers a promising solution by synchronizing N supply with crop demand. Further enhancement in N use efficiency (NUE) can be achieved by integrating nano-fertilizers, which to some extent allow for reduced N application rates without compromising crop performance. In this context, a field experiment was conducted at the ICAR Research Complex, Meghalaya, to evaluate the effects of PNM and nano-urea (NU) on rice productivity, root dynamics and micronutrient uptake. Results indicated that SPAD (Soil plant analysis development) and LCC (Leaf color chart) based N management save N, improves root quality, micronutrient uptake and grain yield, which was comparable to soil test crop response (STCR) based recommendations, where maximum N was applied. Notably, in the treatment 75% RDN+ 2NU spray, a 25% reduction in the recommended dose of N (RDN) was achievable, as the reduced N dose was effectively supplemented through two foliar sprays of NU, resulting in crop performance comparable to that obtained with 100% RDN. Overall, the study demonstrates that PNM and NU, to some extent, offer a sustainable and efficient strategy for improving rice productivity, root parameters and micronutrient uptake in the NEH region of India.

Keywords: LCC, nano-urea, nitrogen, optimization, SPAD, soil test crop response

Introduction

Rice (*Oryza sativa* L.) is the dominant cereal crop and a primary source of food security and livelihood in the North-Eastern Hill (NEH) region of India, where agriculture sustains a large proportion of the rural population. Although the region contributes only 2.27% to the total rice area and 1.96% to national rice production, rice remains central to regional food systems (Konjengbam *et al.,* 2021). With increasing population pressure, rice production in the NEH region is projected to rise by 10.6%, from 7.5 million metric tons (mt) in 2022 to 8.3 million mt by 2035 (Laitonjam *et al.,* 2022). At the national level, an additional annual increase of nearly 3 mt of rice is required to meet future demand (Das *et al.,* 2016). Cereals generally contain low levels of micronutrients, and since they form the staple diet for the majority of the population, enhancing their micronutrient content is essential to prevent deficiencies (Newell-McGloughlin, 2008). Despite its im-

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portance, rice productivity in the NEH region remains low, largely due to poor nitrogen-use efficiency (NUE) and sub-optimal nutrient management practices. Conventional blanket application of nitrogen (N) fertilizers often fails to synchronize N supply with crop demand, leading to inefficient use. It is estimated that nearly 70% of the applied N is lost through leaching, volatilization, runoff, and denitrification, leaving only about 30% available for crop uptake. Nitrogen deficiency is widespread in most soils, and improving its efficiency use is critical, as N is the key yield-limiting nutrient in rice production (Ghosh and Dass, 2019). Proper N management is essential not only for photosynthesis and metabolic functions but also for regulating root architecture and overall crop productivity (Wang *et al.,* 2022). The challenges of N management are further intensified in the NEH region due to high rainfall, acidic soils, and soil erosion, which exacerbate nutrient losses and reduce fertilizer use efficiency (Harish *et al*., 2019; 2021). Addressing these constraints requires a shift from blanket fertilizer recommendations to need-based, site-specific, and real-time nutrient management approaches. In this context, precision nutrient management (PNM) tools such as the Leaf Color Chart (LCC), SPAD meter, Green Seeker, Crop Manager, and Nutrient Expert offer promising solutions by enabling timely and accurate N application based on crop demand. Recent studies highlight the effectiveness of these tools in improving rice productivity and NUE. Kumar *et al.* (2025) reported that PNM tools enhanced grain yield, net returns, and nutrient-use efficiency by 15, 25, and 15%, respectively, while saving up to 25 kg N ha^{-1}. Similarly, Singh *et al.* (2025) observed that the use of tools such as LCC can save 12–25% of N fertilizer without yield penalty across several cereal crops. In addition, root quality traits and nutrient uptake respond strongly to N availability suggesting that precise optimization of N can alter root morphology (Deng *et al*., 2020) and improve micronutrient uptake in beneficial ways (Shahi *et al*., 2020). Thus, adoption of PNM tools represents a sustainable pathway to enhance rice productivity, reduce N losses, and address the region-specific challenges of rice cultivation in the NEH region of India.

Materials and Methods

The experiment was carried out during the rainy season of 2022 at the ICAR-Research Complex for North Eastern Hill region (ICAR-RC-NEHR) Experimental Farm in Barapani, Meghalaya, India. The crop growing period was characterized by a humid monsoon climate from July to September, followed by a cooler and drier post-monsoon phase from October onwards. Maximum temperature remained fairly stable (27–30 °C) during July–September and declined gradually to about 22–25 °C by November–December. Relative humidity was consistently high during the monsoon (88–93%). The experimental soil was red lateritic, strongly acidic (pH 4.7), with sandy-clay loam texture, low to moderate N (237 kg ha^{-1}), low available P (6.5 kg ha^{-1}), and high K (285) kg ha^{-1}. Rice variety Shahsarang 1 was sown on 11th July and transplanted after one month. The experiment had eight treatments replicated thrice, set up using a Randomized Complete Block Design (RCBD). Treatments comprised: T_1, control (no N); T_2, RDN; T_3, STCR; T_4, 30% RDN + SPAD ≤ 35; T_5, 30% RDN basal + SPAD ≤ 37; T_6, 30% RDN basal + LCC <4; T_7, 75% RDN basal + nano-urea @ 500 ml acre^{-1} (two sprays at 30 and 50 DAT); and T_8, 50% RDN basal + nano-urea @ 500 ml acre^{-1} (two sprays at 30 and 50 DAT). The STCR equation used was (2.82 × Target yield – 0.13 × Soil N, where target yield was 35 q ha^{-1}) (Singh *et al*., 2016). Phosphorus (P_2O_5) @ 60 kg ha^{-1} and potassium (K_2O) @ 40 kg ha^{-1} were applied basally. Under RDN (80 kg ha^{-1} N) and STCR (95 kg ha^{-1} N) based N, one-third of N applied as a basal dose at the time of the transplanting 1/3rd at tillering and 1/3rd at panicle initiation was applied. In the SPAD and LCC-based N treatment, 30% RDN was applied basally, followed by 20 kg N ha^{-1} whenever LCC or SPAD readings approached their predefined critical limits (LCC <4 and SPAD ≤ 35 or ≤ 37). Readings were taken at regular intervals. Irrigation was not given due to well distributed rainfall throughout the growing period. At 50% flowering, root parameters were recorded from five randomly selected hills in the sample rows. A soil core (10 cm length × 7 cm diameter) was used to carefully extract the hills, and the roots were gently washed under running water. Root volume (cc) was determined by the water displacement method using a measuring cylinder, while root length (cm) was measured from the base to the tip using a ruler and the total root length was calculated. Grain and straw yield from net plots were obtained after cutting and threshing the plant, which was then converted into t ha^{-1}. According to the method outlined by Rana *et al.* (2014), the amounts of Fe, Zn, Mn, and Cu in the dry matter of rice grains and straw were determined. By multiplying the grain and straw yield of rice with their respective concentrations the uptake of Zn, Mn, Cu, and Fe in rice grains and straw was estimated and expressed in g ha^{-1}. The harvest index was calculated with the formula given by Singh and Stoskopf (1971):

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

The data for each parameter were analyzed using analysis of variance (ANOVA) appropriate for a completely randomized block design as described by Gomez and Gomez (1984).

Results and Discussion

Root dynamics

Root growth parameters differed significantly among treatments, highlighting the profound influence of nitrogen management strategies on below-ground biomass allocation and architectural development in rice grown on acidic red lateritic soils. The STCR treatment recorded the highest root length (32 cm), root volume (90 cc hill^{-1}), and root dry weight (13 g hill^{-1}), which were statistically at par with precision nutrient management (PNM)-based treatments (30% RDN + SPAD ≤ 35, 30% RDN + SPAD ≤ 37, and 30% RDN + LCC < 4) (Table 1). All these treatments were significantly superior to the conventional recommended dose of nitrogen (RDN) and the absolute control. Specifically, root volume increased by 25% under STCR and by 11.1–25% under precision N management treatments, while root dry weight increased by 30% under STCR and 10–30% under precision N management treatments compared to RDN. These findings underscore the critical importance of synchronizing N supply with crop demand phases to optimize root plasticity in the challenging edaphic environment of the NEH region (Rajanna *et al*., 2023), where red lateritic soils present inherent constraints including high bulk density, acidity-induced aluminum toxicity, and nutrient fixation capacity that restrict root exploration. The substantial improvement in root morphological attributes under STCR and PNM regimes can be attributed to the temporal optimization of nitrogen availability during critical tillering and panicle initiation stages, thereby preventing the early-season luxury consumption and subsequent deficiency phases characteristic of conventional blanket fertilizer recommendations. Enhanced root length and volume under these precision approaches facilitate deeper soil penetration and greater exploitation of subsoil moisture and nutrient reserves, particularly crucial in rainfed upland rice ecologies where intermittent moisture stress exacerbates the low inherent fer-

Table 1. Effect of different nitrogen management practices on root parameters of rice at maximum flowering stage

Treatment	Root length (cm)	Root volume (cc hill^{-1})	Root dry wt.(g hill^{-1})
Control	18	49	7
RDN	25	72	10
STCR	32	90	13
30%RDN+ SPAD≤35	32	89	13
30%RDN+SPAD≤37	32	90	13
30%RDN+LCC<4	29	80	11
75%RDN+2NU	25	71	10
50%RDN+2NU	22	63	9
SEm±	2.32	6.51	0.86
CD (*P*=0.05)	7.05	19.74	2.62

Note: RDN: Recommended dose of N; STCR: Soil test crop response; SPAD: Soil plant analysis development; LCC: Leaf color chart; NU: Nano-urea tility of lateritic soils (Harish *et al.,* 2019; 2025). The development of robust root systems, as evidenced by the 30% increase in root dry weight under STCR, establishes the foundational infrastructure for efficient acquisition of immobile nutrients such as phosphorus, zinc, and iron, which exhibit severe fixation and limited bioavailability in acidic red lateritic pedogenic environments (Lynch, 2011; Kumar and Choudhary, 2023).

Compared to RDN, the treatment receiving 75% RDN supplemented with two nano-urea sprays showed comparable root quality parameters, indicating that substitution of 25% soil-applied N with foliar nano-urea applications-maintained root growth architecture similar to full conventional fertilization. This observation suggests that nano-scale urea particles facilitate efficient N assimilation through foliar pathways, potentially reducing the metabolic carbon cost associated with excessive root proliferation for soil N foraging while maintaining adequate root biomass for mechanical support and water uptake. However, both the RDN and 75% RDN + nano-urea treatments were significantly inferior to STCR and SPAD/LCC-based PNM treatments, emphasizing that real-time nitrogen management based on SPAD or LCC provides superior synchronization with plant physiological demand compared to fixed-schedule application regimes, irrespective of the fertilizer source or formulation. Conversely, the treatment receiving 50% RDN + two nano-urea sprays exhibited substantial reductions in root development, with RDN demonstrating 13.6%, 14.3%, and 11.1% greater root length, volume, and root dry weight, respectively, compared to this sub-optimal-input treatment. This disparity suggests that insufficient basal N availability below a critical threshold compromises early root establishment and branching density, which foliar supplementation alone cannot remediate, particularly in the coarse-textured, low-organic-matter lateritic soils characterizing the experimental site.

The root system constitutes a vital rice organ that performs numerous physiological functions including water and nutrient acquisition, and biosynthesis of cytokinins and other growth regulators that mediate shoot growth and grain filling processes (Wu *et al.,* 2014). Root morphological traits are directly connected with dry matter accumulation and grain yield, particularly in resource-limited environments where deep and dense root systems confer adaptive advantages against combined abiotic stresses prevalent in the NEH region. Consequently, a robust connection existed between the rice root system architecture, optimized N management, and ultimate yield realization (Fageria *et al.,* 2011; Zhang *et al.,* 2011; Chen *et al.,* 2020; Kaysar *et al*., 2022). The enhanced root proliferation observed under precision management systems likely promotes greater rhizosphere acidification through organic acid exudation, thereby increasing the solubilization and uptake of micronutrients such as zinc and iron that are typically rendered unavailable in the high-pH micro-environments of intensively fertilized rice soils or fixed in acidic lateritic matrices (Dobermann, 2007; Pradhan *et al*., 2025).

Table 2. **Effect of different nitrogen management practices on micronutrient uptake in rice grain and straw**

Treatment	Fe-uptake (g ha^{-1})		Zn-uptake (g ha^{-1})		Cu-uptake (g ha^{-1})		Mn-uptake (g ha^{-1})	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Control	245	725	61	242	25	91	69	259
RDN	341	866	92	315	37	118	99	319
STCR	392	966	118	391	45	147	122	382
30%RDN+ SPAD≤35	363	878	102	332	40	125	110	336
30%RDN+SPAD≤37	380	898	109	345	44	130	116	349
30%RDN+LCC<4	353	891	97	329	39	123	106	337
75%RDN+2NU	334	871	87	305	35	114	97	319
50%RDN+2NU	312	839	78	281	32	105	89	300
SEm±	12	31	7.98	24.56	2.58	8.77	6.37	25
CD (*P*=0.05)	38	93	24.19	74.48	7.82	26.61	19.32	NS

Note: RDN: Recommended dose of N; STCR: Soil test crop response; SPAD: Soil plant analysis development; LCC: Leaf color chart; NU: Nano-urea

Rice yield

Compared to RDN, the STCR approach increased grain yield by 12.0%, straw yield by 8.8%, and biological yield by 10.2%, while harvest index improved marginally (Fig. 1), suggesting that the additional biomass synthesized under site-specific N management was efficiently translocated to the reproductive structures rather than merely accumulating as vegetative growth. This substantial enhancement in grain productivity under STCR reflects the optimization of N availability during critical growth stages, particularly panicle initiation and flowering, when nutrient deficiency in conventional fixed-dose applications often leads to spikelet sterility and reduced grain filling duration in the NEH region (Harish *et al*., 2019; 2021). The PNM treatments enhanced grain yield by 3.7–9.5% and biological yield by 1.7–5.2% over RDN, with a consistently higher harvest index (Fig. 1), indicating that real-time monitoring of leaf N status enabled more efficient canopy photosynthesis and source-sink relationships that favored grain development over excessive vegetative luxuriance, a common physiological disorder in conventional high-dose N applications. In contrast, the treatment receiving 75% RDN supplemented with 2 nano- urea sprays recorded grain and biological yields comparable to RDN, demonstrating that foliar application of nano-fertilizers can effectively compensate for moderate reductions in soil-applied N while maintaining yield levels similar to standard recommendations. However, the treatment receiving 50% RDN + 2NU sprays resulted in 8.1% lower grain yield and 5.3% lower biological yield than RDN, highlighting that nano-urea foliar sprays, despite their high use efficiency and rapid assimilation through leaf cuticles, cannot fully substitute for basal soil N below a critical threshold required for establishing the fundamental metabolic machinery and initial tillering in rice. Specifically, the application of 75% RDN basal + 2NU sprays increased grain yield, straw yield, biological yield, and harvest index by 6.0%, 3.2%, 4.4%, and 1.7%, respectively, compared to 50% RDN basal + 2NU sprays, establishing an optimal substitution rate where 25% of soil N can be replaced by foliar nano-urea without compromising productivity, whereas 50% substitution proves inadequate for sustaining yield potential in these nutrient-depleted soils (Harish *et al*., 2019; 2021).

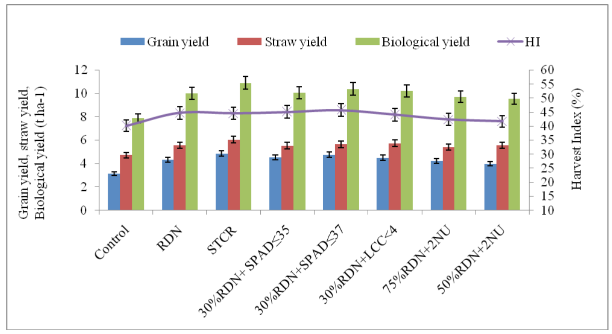

Fig. 1. Effect of different nitrogen management practices on yield and harvest index of rice.

The absolute control treatment, receiving no N fertilization, exhibited the lowest yield followed by the 50% RDN basal + 2NU sprays treatment, underscoring the severe N limitation inherent in the experimental site's red lateritic soil, where native mineralization rates are insufficient to support even moderate rice productivity without external nutrient inputs. When evaluated relative to the control, the STCR, SPAD≤37, SPAD≤35, LCC<4 and RDN based N-application enhanced grain yield by 54%, 51%, 44%, 43% and 37.6%, respectively, over control, demonstrating that even conventional fertilization provides substantial relief from nutrient constraints, though precision approaches offer significantly superior exploitation of the cultivar's genetic yield potential (Rajpoot *et al*., 2021; Kumar *et al*., 2021). The gradient of yield improvement from RDN (37.6%) through LCC<4 (43%) and SPAD-based treatments (44-51%) to STCR (54%) illustrates the progressive benefits of increasingly sophisticated N management strategies, with the 16.4% point advantage of STCR over RDN translating to substantial economic returns in resource-poor farming systems.

Overall, PNM approaches utilizing SPAD and LCC demonstrate superior agronomic effectiveness compared to conventional RDN in enhancing root growth, biomass accumulation, and ultimately grain yield, primarily by ensuring synchronized N availability with crop demand during phenological phases of maximum nutrient uptake efficiency. The significant increase in yield under SPAD-based N application was associated with the strong correlation between SPAD values and tissue N status (Habibi *et al.,* 2025), enabling precise temporal calibration of fertilizer application that minimizes leaching losses in the high-rainfall, porous lateritic environment while maximizing recovery efficiency (Rajanna *et al*., 2023). Although the STCR treatment produced the highest absolute yield, it required a substantial quantity of fertilizers; therefore, PNM treatments, which utilize lower total N doses but achieve comparable yields with superior nutrient use efficiency, offer a more sustainable and economically viable alternative for smallholder farmers in the NEH region (Mohanta *et al.,* 2021; Pratap *et al*., 2022; Sadhukhan *et al.,* 2023). These findings suggest that optimizing N timing and splitting based on real-time crop monitoring can decouple high yield achievement from excessive fertilizer consumption, addressing both food security imperatives and environmental stewardship in fragile mountain agro-ecosystems.

Micronutrient (Fe, Zn, Cu, Mn) acquisition

Micronutrient uptake in both grain and straw was markedly influenced by N management practices. STCR recorded the highest uptake of all micronutrients, followed closely by PNM based treatments. Among PNM approaches, 30% RDN + SPAD ≤ 37 consistently showed higher uptake than SPAD ≤ 35 and LCC <4, and remained comparable with STCR. Compared to RDN, Fe, Zn, Cu, and Mn uptake was increased by approximately 6–14%, 11–18%, 8–19%, and 7–17%, respectively, under PNM treatments, indicating improved nutrient acquisition efficiency (Table 2). 75% and 50% RDN + 2 NU showed lower micronutrient uptake than SPAD and LCC based PNM treatments, though values were comparable with RDN. Compared to 50% RDN + 2 NU, RDN increased micronutrient uptake in grain by 9.3% (Fe), 17.9% (Zn), 15.6% (Cu), and 11.2% (Mn), while straw uptake increased by 3.2% (Fe), 12.1% (Zn), 12.4% (Cu), and 6.3% (Mn) (Table 2). Similarly, 75% RDN + 2 NU recorded higher uptake than 50% RDN + 2 NU, with increases of 7.1% (Fe), 11.5% (Zn), 9.4% (Cu), and 9.0% (Mn) in grain and 3.8–8.5% in straw. Even though STCR and PNM had comparable uptake, the advantage is that the PNM requires comparatively less fertilizer input. The higher uptake of micronutrients under PNM treatments can be attributed to optimum and need-based N application, which maintained an adequate N status throughout critical growth stages. The optimized N supply enhanced root activity and nutrient absorption efficiency and facilitated better translocation of micronutrients from soil to plant tissues (Kutman *et al.,* 2010; Barunawati *et al.,* 2013). The PNM based N application synchronized N availability with crop demand, thereby improving micronutrient uptake efficiency without excessive fertilizer input.

Conclusion

The study demonstrated that nitrogen management practices significantly influenced root characteristics, yield, and micronutrient uptake in rice. Precision nitrogen management (PNM) tools enhanced root growth, yield, and micronutrient uptake comparable to STCR while using lower nitrogen doses. SPAD with a threshold of 37 emerged as a suitable option, demonstrating consistent and reliable performance among the precision N management treatments. PNM based N application saved 31 kg N ha^{-1} without yield penalty compared to STCR. In addition, two nano-urea sprays can be effectively used as a supplement to 75% RDN. Further, it was revealed that 2 NU sprays were inadequate to offset a 50% reduction in RDN, as evidenced by significantly lower crop N response under the 50% RDN + 2NU treatment. Overall, PNM tools can be used as a viable and efficient alternative to conventional fertilizer-intensive practices in the NEH region, enabling optimal crop performance with reduced nitrogen input.

References

Barunawati, N., Giehl, R. F. H., Bauer, B. and Wirén, N. V. 2013. The influence of inorganic nitrogen fertilizer forms on micronutrient retranslocation and accumulation in grains of winter wheat. *Frontiers in Plant Science,* **4**: 320.

Chen, J., Liu, L., Wang, Z., Zhang, Y., Sun, H., Song, S., Bai, Z., Lu, Z. and Li, C. 2020. N-fertilization increases root growth and coordinates the root-shoot relationship in cotton. *Frontiers in Plant Science*, 11: 880.

Dass, A., Chandra, S., Choudhary, A.K., Singh. and Sudhishri, S. 2016. Influence of field re-ponding pattern and plant spacing on rice root–shoot characteristics, yield, and water productivity of two modern cultivars under SRI management in Indian Mollisols. *Paddy Water Environment*, **14**: 45–59.

Deng, J., Feng, X., Wang, D., Lu, J., Chong, H., Shang, C., Liu, K., Huang, l., Tian., X. and Zhang, Y. 2020. Root morphological traits and distribution in direct-seeded rice under dense planting with reduced nitrogen. *Plos One*, **15**(9): e0238362.

Dobermann, A. 2007. Nutrient use efficiency–measurement and management.IFA International Workshop on Fertilizer Best Management Practices, 7–9 March 2007, Brussels, Belgium.

Fageria, N. Santos, A. and Coelho, A. 2011. Growth, yield and yield components of lowland rice as influenced by ammonium sulfate and urea fertilization. *Journal of Plant Nutrition*, **34**(3): 371-386.

Ghosh, A.P. and Dass, A. 2019. Precision N-management in maize cultivars under variable growing environments: Effects on plant growth, NDVI and leaf N. *e-planet*, **17(**2): 98-105.

Gomez, K.A. and Gomez, A.A. 1984. Statistical Procedures for Agricultural Research. John Wiley and Sons, New York.

Habibi, N., Sharaf, Z., Fakoor, M. Y., Aryan, S., Mahmoodzada, A. B., Fakhri, A. and Faqiri, S. M. 2025. Nitrogen matters: assessing the effects of N-fertilization on maize growth and grain productivity. *Nitrogen*, **6**(4): 115.

Harish, M.N., Choudhary, A.K., Dass, A., Singh, V.K., Rajanna, G.A., Bana, R.S., Paramesh, V., Varatharajan, T., Bhupenchandra, I., Sadhukhan, R., Kumar, A., Sachin, K.S., Teli, K.G., Singh, S.R.K., Raut, A.A., Sannagoudar, M.S., Muniyappa, L. and Prasad, H.P.N. 2025. Double zero-tilled bed-planting and optimized P-fertilization in maize-wheat rotation: An empirical investigation on root architecture, carbon-phosphorus-dynamics and soil-carbon-pools. *Journal of Environmental Management*, **392**: 126668.

Harish, M.N., Choudhary, A.K., Singh, Y.V., Pooniya, V., Das, A. Varatharajan, T. and Babu, S. 2019. Influence of varieties and nutrient management practices on productivity, nutrient acquisition and resource-use efficiency of rice (*Oryza sativa*) in north-eastern hill region of India. *Indian Journal of Agricultural Sciences*, **89**(2): 367–370.

Harish, M.N., Choudhary, A.K., Singh, Y.V., Pooniya, V., Das, A., Babu, S., Dass, A. and Varatharajan, T. 2021. Nutrient management practices for improved crop and water productivity, grain quality and energy productivity of promising rice cultivars in Eastern Himalayas. *Journal of Environmental Biology*, **42**(2): 309-318.

Kaysar, M.S., Sarker, U.K., Monira, S., Hossain, M.A., Haque, M.S., Somaddar, U., Saha, G., Chaki, A.K. and Uddin, M.R. 2022. Dissecting the relationship between root morphological traits and yield attributes in diverse rice cultivars under subtropical condition. *Life*, 12: 1519.

Konjengbam, N. S., Mahanta, M. and Lyngdoh, A. A. 2021. Rice cultivation-A way of life for the people of north eastern hill region of India. *Integrative Advances in Rice Research*, 131-144.

Kumar, A. and Choudhary, A.K. 2023. Food-energy-carbon nexus of Himalayan okra–pea cropping system: Impacts of AM-fungi, precision phosphorus and irrigation regimes in an acid Alfisol. *Science of the Total Environment*, **899**: 165589.

Kumar, A., Rana, K.S., Choudhary, A.K., Bana, R.S., Sharma, V.K., Prasad, S., Gupta, G., Choudhary, M., Pradhan, A., Rajpoot, S.K., Kumar, A., Kumar, A. and Tyagi, V. 2021. Energy budgeting and carbon footprints of zero-tilled pigeonpea–wheat cropping system under sole or dual crop basis residue mulching and Zn-fertilization in a semi-arid agro-ecology. *Energy*, **231**: 120862.

Kutman, U. B., Yildiz, B. and Cakmak, I. 2011. Effect of nitrogen on uptake, remobilization and partitioning of Zn and Fe throughout the development of durum wheat. *Plant and Soil*, **342**: 149-164.

Laitonjam, N., Singh, N. U., Chakraborty, D., Paul, P., Biam, K. P., Gowda, C., Dkhar, H. and Mishra, V. K. 2022. Rice production in Northeast India: Decomposition and trend analysis. *Indian Journal of Hill Farming*, **35**: 120-128.

Lynch, J. P. 2011. Root phenes for enhanced soil exploration and phosphorus acquisition: Tools for future crops. *Plant Physiology*, **156**: 1041–1049.

Mohanta, S., Banerjee, M., Malik, G. C., Shankar, T., Maitra, S., Ismail, I. A., Dessoky, E. S., Attia, A. O. and Hossain, A. 2021. Productivity and profitability of kharif rice are influenced by crop establishment methods and N-management in lateritic belt of subtropical region. *Agronomy,* **11**7: 1280.

NewellMc Gloughlin, M. 2008. Nutritionally improved agricultural crops. *Plant Physiology*, **147**: 939–953.

Pradhan, A., Rana, K.S., Choudhary, A.K., Bana, R.S., Thapa, S., Dash, A.K., Singh, J.P., Kumar, A., Harish, M.N., Hasanain, M. and Kumar, A. 2025. Dual-crop basis residue-retained bed-planting and zinc fertilization lead to improved food-energy-water-carbon nexus in pearl millet-wheat cropping system in semi-arid agro-ecologies. *Renewable and Sustainable Energy Reviews*, **215**: 115579.

Pratap, V., Dass, A., Dhar, S., Babu, S., Singh, V.K., Singh, R., Krishnan, P., Sudhishri, S., Bhatia, A., Kumar, S., Choudhary, A. K., Singh, R., Kumar, P., Sarkar, S.K., Verma, S. K., Kumari, K. and San, A.A. 2022. Co-implementation of tillage, precision nitrogen and water management enhances water productivity, economic returns, and energy-use efficiency of direct-seeded rice. *Sustainability,* **14**(11234): 1-20.

Rajanna, G.A., Dass, A., Singh, V.K., Choudhary, A.K., Venkatesh, P., Babu, S., Upadhyay, P.K., Sannagoudar, M.S., Ajay, B.C. and Reddy, V.K. 2023. Energy and carbon budgeting in a soybean–wheat system in different tillage, irrigation and fertilizer management practices in south-Asian semi-arid agroecology. *European Journal of Agronomy*, **148**: 126877.

Rajpoot, SK., Rana, D.S. and Choudhary, A.K. 2021. Crop and water productivity, energy auditing, carbon footprints and soil health indicators of *Bt*-cotton transplanting led system intensification. *Journal of Environmental Management*, **300**: 113732.

Rana, K.S., Choudhary, A.K. Sepat, S., Bana, R.S. and Dass, A. 2014. *Methodological and Analytical Agronomy* Post Graduate School, Indian Agricultural Research Institute, New Delhi, India. pp 276.

Sadhukhan, R., Kumar, D., Sen, S., Sepat, S., Ghosh, A., Shivay, Y. S., Meena, M. C., Anand, A., Kumar, R., Sharma, L. D., Patra, K., Pratap, V., Alsuhaibani, A. M., Gaber, A. and Hossain, A. 2023. Precision nutrient management in zero-till direct-seeded rice influences the productivity, profitability, nutrient, and water-use efficiency as well as environmental footprint in Indo Gangetic plain of India. *Agriculture*, **13**(4): 784.

Shahi, U. P., Singh, V. K., Kumar, A., Singh, P., Dhyani, B. P. and Singh, A. 2020. Effect of site-specific nutrient management on productivity, soil fertility and nutrient uptake in maize. *Indian Journal of Agronomy*, **65**(4): 432-438.

Singh, I.D. and Stoskopf, N.C. 1971. Harvest index in cereals. *Agronomy Journal,* 63: 224–226.

Singh, K. C., Vishnoi, M., Fayaz, S., Parihar, P., Patyal, D., Amjid, S.,Mir, Y.H. and Tutlani, A. 2025. Leaf Colour Chart (LCC) a reliable tool for N-management: A comprehensive review. *Journal of Scientific Research and Reports*, **31**(9): 743-754.

Singh, S.L., Brajendra, and Patiram. 2016. Soil test crop response-based fertilizer recommendations in Meghalaya. *Progressive Research,* **11**(3): 2083-2089.

Wang, B., Zhou, G., Guo, S., Li, X., Yuan, J. and Hu, A. 2022. Improving nitrogen use efficiency in rice for sustainable agriculture: strategies and future perspectives. *Life,* **12**(10): 1653.

Wu, W. and Cheng, S. 2014. Root genetic research, an opportunity and challenge to rice improvement. *Field Crops Research*, 165: 111-124.

Zhang, J., Zhu, T., Cai, Z and Muller, C. 2011. N-cycling in forest soils across climate gradients in Eastern China. *Plant and Soil,* **342**(1): 419-432.