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Nutrient expert®-rice: A tool for increasing crop yields, farm profit and improves yields while balancing fertilizers use

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Abstract

Rice (*Oryza sativa* L.) constitutes the backbone of food security in India, serving as the primary source of dietary calories for more than half of the population (FAO, 2023; Government of India, 2022) [14]. Rice productivity yet in many rice-based systems remains constrained by imbalanced fertilizer use and generalized nutrient recommendations that overlook field-level variability in soil fertility, climate, and crop management. Site-specific nutrient management (SSNM) has been proposed as an effective framework to address these limitations by aligning nutrient supply with crop demand in space and time. This review synthesizes evidence from multi-location on-farm and on-station studies across Nepal and India to evaluate the agronomic, economic, and environmental performance of Nutrient Expert®-Rice (NE), an ICT-based decision support tool designed to operationalize SSNM principles in farmers' fields.

The Pooled results from diverse agro-ecological regions indicate that NE-based SSNM consistently outperformed farmers' fertilizer practices, government/state fertilizer recommendations, and blanket recommended doses (Dobermann & Witt, 2004; Pampolino *et al.*, 2012; Majumdar *et al.*, 2014) [9, 10, 11, 19, 25]. Across locations, NE-based SSNM achieved higher grain yields (5.1-7.0 t ha⁻¹) compared with farmers' practices (3.8-5.2 t ha⁻¹), supported by improvements in key yield-attributing characters such as tiller density, panicle number, grains per panicle, and grain weight (Budhathoki *et al.*, 2018; Amgain *et al.*, 2021; Singh *et al.*, 2019; Mannade *et al.*, 2017) [3, 21, 35]. Economic analyses revealed substantial gains in net returns and benefit-cost ratios under NE, primarily driven by yield enhancement and improved nutrient use efficiency rather than increased fertilizer input (Qureshi *et al.*, 2016; Mandal *et al.*, 2016; Jat *et al.*, 2018) [18, 20, 28]. NE-based recommendations reduced nitrogen application by 15-35% while correcting chronic potassium under-application, resulting in higher agronomic efficiency and reduced greenhouse gas emissions (Dobermann & Witt, 2004; Sapkota *et al.*, 2021; Sadhukhan *et al.*, 2023) [9, 10, 11, 31, 32].

Validated case studies spanning contrasting soils, climates, varieties, and crop establishment methods including transplanted and direct-seeded rice confirm the robustness and scalability of NE-based SSNM. Overall, the evidence demonstrates that Nutrient Expert®-Rice provides a practical, scientifically validated pathway to narrow yield gaps, enhance farm profitability, and promote balanced and environmentally responsible fertilizer use. Wider adoption of NE-based SSNM can support sustainable intensification of rice and rice-wheat systems in South Asia and comparable agro-ecologies worldwide (Cassman *et al.*, 2003; Dobermann & Witt, 2004; Pampolino *et al.*, 2012; Sapkota *et al.*, 2021) [5, 9, 10, 11, 25, 32]. Nutrient Expert®-based Site-Specific Nutrient Management (NE-SSNM) provides a scientifically robust and practical alternative to farmers' fertilizer practices and blanket government recommendations in rice systems.

Keywords: Rice production, India agriculture, dietary calories, kharif rice

Introduction

Rice (*Oryza sativa* L.) constitutes the backbone of food security in India, serving as the primary source of dietary calories for more than half of the population (FAO, 2023; Government of India, 2022) [14]. India consistently ranks as the world's second-largest rice producer, cultivating the crop over approximately 44-45 million ha with an annual production exceeding 130 million tonnes (FAOSTAT, 2023; Ministry of Agriculture and Farmers Welfare, 2023) [14, 24]. According to the Ministry of Agriculture and Farmers Welfare

(2024), Kharif rice production during the 2022-23 crop year alone was estimated at about 110.5 million tonnes, underscoring the central role of rice in the national agrarian economy. Despite this substantial output and sustained growth in total production, national average rice productivity remains modest, at approximately 3.0-3.2 t ha⁻¹, and falls considerably short of attainable yields achieved under optimized agronomic and nutrient management practices. This disparity highlights the persistence of significant yield gaps across Indian rice systems (Cassman *et al.*, 2003; Dobermann *et al.*, 2004) [5, 9, 10, 11]. With limited scope for horizontal expansion of cultivated land, future increases in rice production must therefore be driven primarily by improvements in productivity and resource-use efficiency. As emphasized by Cassman *et al.*, (2003) [5], “meeting future food demand will require producing more grain per unit of land, water, and nutrient input, while minimizing adverse environmental impacts.”

India's fertilizer economy has mirrored this expansion in rice cultivation. With an increasing reliance on mineral fertilizers over past decades, India has solidified its position as the second-largest consumer of fertilizer nutrients globally, accounting for nearly 15% of total global consumption (PIB, 2025). Government data indicates that during the 2023-24 fiscal year, total fertilizer consumption in India reached a record 601 Lakh Metric Tonnes (LMT), a substantial portion of which was utilized for cereal crops, particularly rice (Department of Fertilizers, 2024) [8]. These statistics demonstrate the massive scale of nutrient inputs but also highlight systemic imbalances. Nitrogen (N) is predominantly applied at rates far exceeding those of phosphorus (P) and potassium (K), disrupting the optimal 4:2:1 nutrient ratio recommended for Indian soils. As highlighted by the Indian Council of Agricultural Research (ICAR), “policies which encourage the use of only one type of fertilizer, particularly N alone, can lead to a decline in productivity and reduction in response to nitrogen,” thereby threatening long-term soil health and sustainability (Tiwari *et al.*, 2023) [38].

Mineral fertilizers, particularly nitrogen (N), phosphorus (P), and potassium (K), have played a central role in enhancing rice productivity in India. However, fertilizer use in farmers' fields is frequently characterized by excessive, imbalanced, and inefficient application, with a strong bias toward nitrogenous fertilizers. National fertilizer consumption data consistently indicate a distorted N: P: K use ratio relative to crop demand. Fertilizer recommendations provided through government or state extension systems are largely based on blanket recommended doses of fertilizers (RDF), which do not adequately account for field-specific soil fertility, crop establishment methods, or seasonal variability. Moreover, fertilizer application in rice is often poorly synchronized with crop nutrient demand, with limited adoption of split application strategies. Dobermann and Cassman (2002) [12] highlighted that “yield and nitrogen-use efficiency in rice are maximized only when nitrogen supply is closely matched with crop demand in both time and quantity.”

In reality, nutrient management decisions by farmers are predominantly guided by experience, perceptions of yield response, and access to fertilizers, rather than by scientific assessment of soil nutrient supply and crop requirement. Consequently, nutrient inputs are rarely balanced and are

often driven more by resource availability than by agronomic principles. Pampolino *et al.*, (2012) [25] reported that fertilizer practices in Asian rice systems are “highly variable and frequently suboptimal, resulting in low fertilizer-use efficiency and diminished economic returns.” Such practices contribute to declining factor productivity of fertilizers and widening yield gaps.

The challenge is further compounded by pronounced spatial and temporal variability in soil fertility across rice-growing landscapes. Differences in soil texture, organic matter status, cropping history, residue management, irrigation regime, and crop establishment methods (puddled transplanted rice vs. direct-seeded rice) create substantial heterogeneity in indigenous nutrient supply. Dobermann *et al.*, (2004) [9, 10, 11], noted that “field-to-field variability in soil nutrient availability is the norm rather than the exception in intensive rice-based systems.” Under such conditions, farmers are unable to accurately predict appropriate fertilizer rates, leading to both under- and over-application of nutrients.

Inefficient fertilizer use has direct economic implications for rice farmers. Excessive application of fertilizers, particularly nitrogen, increases the cost of cultivation without proportionate yield gains, thereby reducing profitability. Conversely, inadequate or imbalanced fertilization constrains yield potential and grain quality. Witt *et al.*, (2009) demonstrated that fertilizer application beyond the economically optimal rate results in sharply declining marginal returns, making rice production more costly and less profitable. These inefficiencies also intensify environmental risks through nutrient losses, including nitrate leaching, ammonia volatilization, and greenhouse gas emissions.

To address these constraints, Site-Specific Nutrient Management (SSNM) has emerged as a scientifically robust framework aimed at tailoring nutrient supply to crop demand in a specific field and season. SSNM seeks to optimize yield, profitability, and nutrient-use efficiency by accounting for indigenous nutrient supply and realistic yield targets. According to IRRI (2006) [17], SSNM “provides a systematic approach to adjusting fertilizer application to match spatial and temporal variability in crop nutrient demand.” While soil test crop response (STCR) approaches and other diagnostic tools contribute valuable insights, their adoption is often limited by high costs, time requirements, and technical complexity, particularly among smallholder farmers.

In this context, Nutrient Expert®-Rice has been developed as a decision-support tool to operationalize SSNM principles in farmers' fields. The tool generates field-specific fertilizer recommendations based on simple inputs related to crop management, previous yields, and local conditions, with or without soil test data. Pampolino *et al.*, (2012) [25] emphasized that Nutrient Expert® offers “a practical and scalable means of implementing SSNM, enabling farmers to achieve higher yields, improved nutrient-use efficiency, and greater profitability compared with conventional fertilizer practices.”

Given the widespread reliance on blanket fertilizer recommendations, rising fertilizer costs, and the urgent need to enhance fertilizer-use efficiency in rice systems, systematic evaluation of Nutrient Expert®-Rice under farmers' field conditions is essential. Therefore, the present study was undertaken to test the hypothesis that site-specific fertilizer recommendations generated through Nutrient

Expert®-Rice can enhance rice yield and farm profitability while balancing fertilizer use, in comparison with conventional farmer practices and recommended blanket fertilizer doses.

Methodology

Nutrient Expert® (NE) Among ICT-based decision support tools, Nutrient Expert® (NE) has emerged as a practical delivery mechanism of SSNM principles for cereals such as rice, wheat, and maize (Satyanarayana *et al.*, 2012) [34]. NE is a computer-based decision support system (DSS) that provides rapid, field-specific fertilizer recommendations for N, P, and K, with or without soil test data (Qureshi *et al.*, 2016) [28]. The tool estimates attainable yield and nutrient requirements based on farmer-provided information on soil type, crop management, residue use, previous yields, climate, and resource availability (Pampolino *et al.*, 2012; Dutta *et al.*, 2014) [13, 25]. Unlike conventional approaches that rely on nutrient omission trials, NE uses proxy indicators to estimate indigenous nutrient supply, making it suitable for regions with limited research and soil testing infrastructure.

The NE tool integrates SSNM with the 4R stewardship concept to develop balanced fertilizer recommendations tailored to specific fields and growing environments. Studies across South Asia have shown that NE-based recommendations enhance crop yield, NUE, and farm profitability while reducing the risk of over or under fertilization (Majumdar *et al.*, 2014; Mandal *et al.*, 2016; Jat *et al.*, 2018; Zhang *et al.*, 2018; Xu *et al.*, 2017) [18, 19, 20, 40, 41]. NE also promotes the integrated use of mineral fertilizers and organic amendments for long-term soil fertility and sustainability (Sapkota *et al.*, 2014, 2021; Parihar *et al.*, 2017) [26, 32].

Nutrient Expert®-Rice (NE-Rice) is a decision-support tool designed to improve crop productivity, profitability, and fertilizer use efficiency while ensuring balanced nutrient supply for rice farmers. Developed by the International Plant Nutrition Institute (IPNI) and a network of partners, NE-Rice is the rice-centric component of the broader Nutrient Expert® initiative, which encompasses maize and wheat versions.

The tool's objective is to recommend nutrient management practices that increase crop yields and farm profitability while minimizing production costs and providing good estimates of nutrient balances, recovery efficiencies, and associated emissions. NE-Rice incorporates location-specific information on rice production such as variety, soil texture, climate data, growing season, and agricultural prices to produce crop- and location-specific fertilizer recommendations under standard management practices (Chivenge *et al.*, 2022) [6].

NE-Rice generates timely, directly applicable, and realistic recommendations within a simple framework. The tool targets water-scarce situations and locations where fertilizer use is low and climatic and agronomic conditions support crop intensification. It operates based on verifiable agronomic data and does not favour specific products or technologies, thereby enabling a wide range of stakeholders to deploy it without technical or organisational barriers (Ali *et al.*, 2018) [2].

We compared three nutrient management strategies (farmer's fertilizer practice- FP, government recommendation -GR, and Nutrient Expert®- NE-based

recommendation), in many farm field/experimental field trials. We used the Nutrient Expert®-Rice tool, for the rice using data from those trials.

1. Literature search and selection strategy a comprehensive review of literature was conducted to evaluate the efficacy of the *Nutrient Expert® (NE) for Rice* decision support tool. The review synthesized findings from field experiments, on-farm trials, and comparative studies conducted across diverse agro-ecological regions in South Asia, specifically focusing on India and Nepal. Key studies were selected based on their focus on:

- Comparisons between NE-based Site-Specific Nutrient Management (SSNM), Farmers' Fertilizer Practices (FFP), Government Recommendations (GR), and State Recommendations (SR).
- Quantitative outcomes regarding grain yield, straw yield, economic profitability (B: C ratio), and Nutrient Use Efficiency (NUE).
- Environmental impact assessments, specifically concerning Greenhouse Gas (GHG) emissions and Global Warming Potential (GWP).

2. Theoretical framework of the review the review analyzes the *Nutrient Expert®* tool through its operational framework as a computer-based Decision Support System (DSS) developed by the International Plant Nutrition Institute (IPNI). The methodology of the tool itself was examined, which operationalizes SSNM principles into user-friendly recommendations without the direct need for soil testing. The review assesses how the tool estimates "attainable yield" and "yield response" using proxy information such as:

- **Growing environment:** Water availability (irrigated/rainfed) and drought/flood risks.
- **Soil fertility indicators:** Soil texture, color, organic matter status, and historical fertilizer use.
- **Crop management:** Crop residue management, previous crop history, and current yield levels.

3. Data Synthesis and Comparative Analysis Data from the selected studies were categorized and synthesized to compare the performance of NE against conventional practices. The analysis focused on:

- **Yield performance:** Aggregating yield differences between NE, FFP, and GR across different locations (e.g., Indo-Gangetic Plains, Terai region of Nepal, Vertisols of Chhattisgarh).
- **Economic analysis:** Comparing net returns and Benefit-Cost (B: C) ratios to determine farm profitability.
- **Nutrient stewardship:** Evaluating the tool's alignment with the "4R Nutrient Stewardship" principles (Right Source, Right Rate, Right Time, Right Place).
- **Environmental metrics:** Reviewing data on N₂O emissions and global warming potential to assess environmental sustainability.

4. Validated case studies The Nutrient Expert® (NE) decision-support tool were validated using multiple location-specific case studies across South Asia, covering contrasting soils, climates, varieties, and crop establishment methods. The review methodology incorporates specific case studies to validate the tool's effectiveness:

- **Western mid-hills, Nepal**
NE was evaluated on the drought-tolerant rice variety *Sukha-3* under rainfed mid-hill conditions at Lamjung. Results showed significantly higher grain yield and profitability under NE compared with Farmers' Fertilizer Practice (FFP) and government recommendations, highlighting the advantage of site-specific nutrient scheduling in moisture-limited environments (Budhathoki *et al.*, 2018; Amgain *et al.*, 2021) [3].
- **Eastern Terai, Nepal**
On-farm trials in Jhapa and Morang districts using the variety *Sambha Mansuli Sub-1* demonstrated that NE-based SSNM increased grain yield by 0.8-1.2 t ha⁻¹ over FFP and government recommendations, along with improved nutrient use efficiency and reduced yield variability (Amgain *et al.*, 2021; Timsina *et al.*, 2014) [3, 37].
- **Indo-Gangetic Plains (IGP), India**
A large dataset comprising 1,594 paired on-farm trials across Punjab, Haryana, and Bihar showed that NE-based SSNM increased rice and wheat yields by 4-8% while reducing nitrogen input by 15-35% and lowering greenhouse gas emissions compared with farmers' practices (Sapkota *et al.*, 2021) [32].
- **Bihar, India**
Field experiments on calcareous soils at RPCAU, Pusa, using rice variety *RAU 1476-4-1* revealed that NE-based SSNM significantly improved grain yield, yield attributes, and nutrient uptake compared with RDF and FFP, confirming the suitability of NE under alkaline and nutrient-imbalanced soils (Singh *et al.*, 2019) [35].
- **Chitwan, Nepal**
Comparative evaluation of a hybrid (*Arize Tej Gold*) and an improved variety (*Radha-4*) showed that NE-based SSNM and LCC-guided N combined with NE-based P and K enhanced tillering, grains per panicle, grain yield, and benefit-cost ratio compared with conventional fertilizer practices (Acharya *et al.*, 2022) [1].
- **New Delhi, India**
Under zero-till Direct-Seeded Rice (DSR) at ICAR-IARI, NE combined with LCC-based nitrogen management improved grain yield, nutrient and water use efficiency, and profitability while reducing N₂O emissions compared with RDF and state recommendations (Sadhukhan *et al.*, 2023) [31].
- **Chhattisgarh, India**
Experiments on Vertisols at Raipur demonstrated that NE-based SSNM produced the highest tiller density, panicle number, grain yield, and straw yield, outperforming RDF and nutrient omission treatments, thereby emphasizing the importance of balanced nutrient supply in heavy clay soils (Mannade *et al.*, 2017) [21].
- **Pantnagar, India**
Long-term evaluations under a rice-wheat cropping system on silty loam Mollisols showed that NE-based SSNM consistently increased grain yield, yield attributes, nutrient use efficiency, and profitability compared with RDF and farmers' practices, with performance comparable to or better than STCR-based recommendations (Qureshi *et al.*, 2016) [28].

Results and Discussion

1. Grain yield response of rice to nutrient expert®-based ssnm across locations

Table 1: Grain yield (t ha⁻¹) of rice under different nutrient management practices across locations

Treatments	Lamjung, Nepal	Jhapa & Morang	IGP (India)	RPCAU, Pusa, Bihar	Fulbari, Chitwan	IARI New Delhi	Raipur, Chhattisgarh	Pantnagar
FFP	4.0-4.2	4.3-4.4	4.5-4.7	4.6	3.8-4.0	4.0-4.2	4.3-4.5	5.0-5.2
GR / State rec.	4.3-4.5	4.7-4.8	-	4.9	4.4-4.5	4.1-4.3	4.7-4.8	5.5-5.6
RDF	-	-	-	4.9	-	4.3-4.4	4.8-4.9	5.6-6.0
NE-based SSNM	5.1-5.2	5.4-5.9	+4-8% over FFP	5.3	5.0-5.2	4.3-4.4	5.0-5.1	6.4-7.0

Table 1: Budhathoki *et al.*, (2018); Amgain *et al.*, (2021) [3] Sapkota *et al.*, (2021) [32] Singh *et al.*, (2019) [35] Acharya *et al.*, (2022) [1]; Sadhukhan *et al.*, (2023) [31] Mannade *et al.*, (2020); Qureshi *et al.*, (2016) [28]

The pooled results across diverse agro-ecological regions clearly demonstrate that Nutrient Expert® (NE)-based Site-Specific Nutrient Management (SSNM) consistently produced higher rice grain yield than Farmers' Fertilizer Practice (FFP), Government/state Recommendations (GR), and blanket Recommended Dose of Fertilizers (RDF) (Table 1). Across locations, grain yield under FFP generally ranged between 3.8 and 5.2 t ha⁻¹, reflecting typical farmer-managed productivity levels reported from Nepal and India (Budhathoki *et al.*, 2018; Amgain *et al.*, 2021; Singh *et al.*, 2019; Mannade *et al.*, 2017) [3, 21, 35]. Government or state fertilizer recommendations resulted in moderately higher yields (4.3-5.6 t ha⁻¹), but still failed to fully exploit site-specific yield potential due to their generalized nature (Qureshi *et al.*, 2016; Acharya *et al.*, 2022) [1, 28].

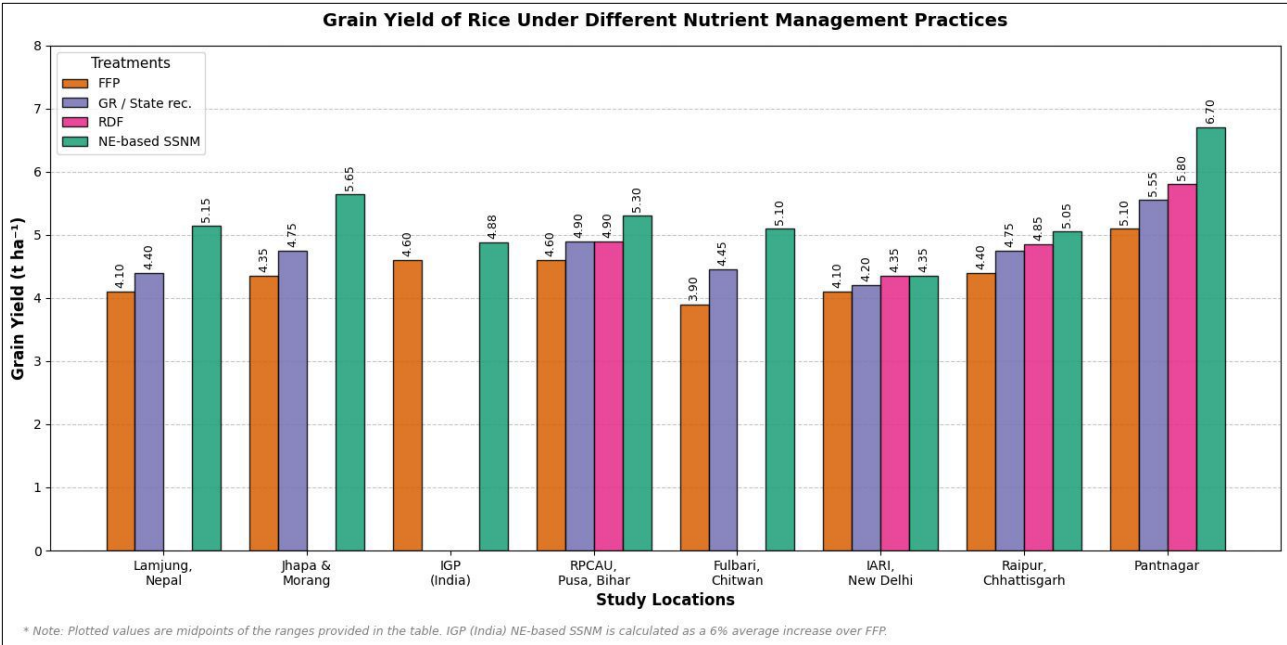
In contrast, NE-based SSNM recorded the highest grain yields across all regions (5.1-7.0 t ha⁻¹), depending on soil

type, climate, crop establishment method, and varietal background (Budhathoki *et al.*, 2018; Amgain *et al.*, 2021; Singh *et al.*, 2019; Qureshi *et al.*, 2016) [3, 28, 35]. The magnitude of yield improvement under NE varied spatially. In low-input and nutrient-constrained environments such as Lamjung, the Eastern Terai of Nepal, Bihar, and Chhattisgarh, yield gains were more pronounced, confirming the ability of SSNM to correct nutrient imbalances common under farmers' practices and blanket recommendations (Budhathoki *et al.*, 2018; Mannade *et al.*, 2017; Singh *et al.*, 2019) [21, 35].

In the Indo-Gangetic Plains (IGP), where baseline productivity is already high, NE-based recommendations still resulted in a 4-8% yield increase over FFP, demonstrating that SSNM remains effective even in intensively managed systems (Sapkota *et al.*, 2021; Sadhukhan *et al.*, 2023) [31, 32]. These consistent yield

advantages across contrasting agro-ecologies validate NE as a robust and scalable decision-support tool for improving rice productivity under diverse production environments. The superior yield performance of NE-based SSNM can be attributed to its field-specific estimation of attainable yield and nutrient demand, which corrects chronic nutrient imbalances common under FFP and blanket recommendations. Farmers’ practices are often

characterized by excess nitrogen and inadequate potassium application, while GR/RDF approaches fail to capture spatial variability in soil nutrient supply (Dobermann and Witt, 2004; Buresh *et al.*, 2010) [4, 9, 10, 11]. By synchronizing nutrient supply with crop demand at critical growth stages, NE improves nutrient uptake efficiency and yield realization (Pampolino *et al.*, 2012; Majumdar *et al.*, 2014) [19, 25].



2. Yield-attributing characters as determinants of yield improvement

Table 2. Pooled yield-attributing characters of rice under different nutrient management practices

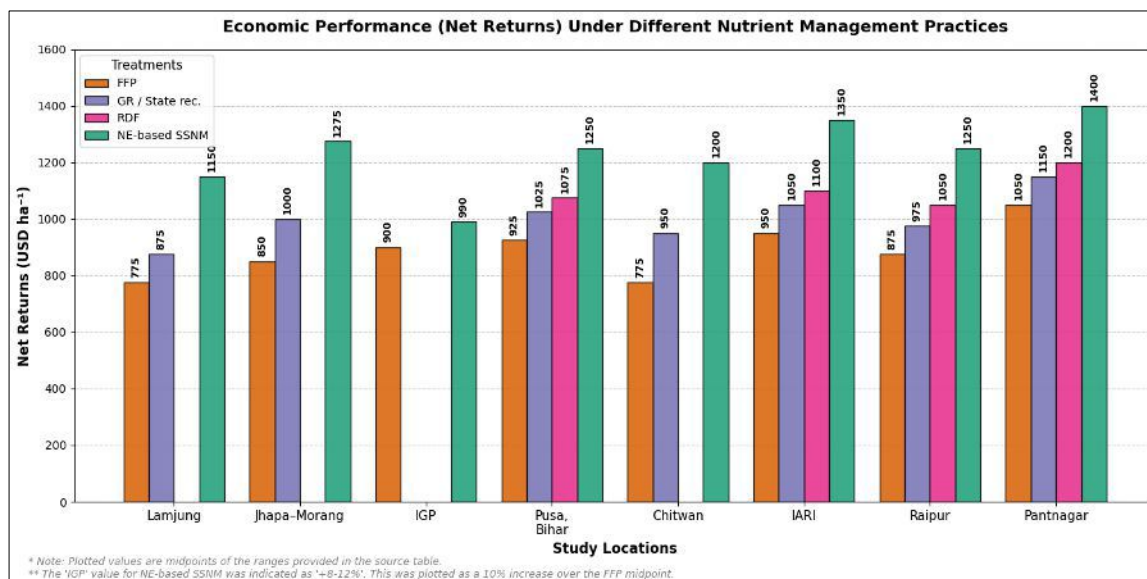
Yield-attributing character	Farmers’ Field Practice (FFP)	Government / State recommendation	RDF	NE-based SSNM / LCC
Tillers (m ⁻²)	260 - 300	300 - 330	310 - 340	350 - 400
Panicles (m ⁻²)	230 - 260	270 - 300	280 - 310	310 - 350
Grains panicle ⁻¹	95 - 110	110 - 120	115 - 125	125 - 135
1000-grain weight (g)	23 - 25	24 - 26	25 - 26	26 - 27

Table 2: amgain *et al.*, (2021) [3]; singh *et al.*, (2019) [35] mannade *et al.*, (2020)

Improvements in grain yield under NE-based SSNM were consistently supported by enhanced yield-attributing characters, confirming that yield gains were physiologically and structurally driven rather than incidental (Table 2) (Budhathoki *et al.*, 2018; Singh *et al.*, 2019; Acharya *et al.*, 2022) [1, 35]. Compared with FFP, NE-based SSNM increased tillers (350-400 m⁻² vs. 260-300 m⁻²) and panicles (310-350 m⁻² vs. 230-260 m⁻²), indicating improved early vegetative vigor and productive tiller survival (Mannade *et al.*, 2017; Qureshi *et al.*, 2016; Amgain *et al.*, 2021) [3, 21, 28]. Similarly, grains per panicle (125-135) and 1000-grain weight (26-27 g) were highest under NE-based SSNM, reflecting better spikelet fertility and grain filling (Singh *et al.*, 2019; Acharya *et al.*, 2022) [1, 35]. These improvements arise from balanced nitrogen and potassium nutrition during

reproductive stages, which enhances assimilate production and translocation to grains (Dobermann *et al.*, 1998; Feng *et al.*, 2007) [9, 10, 11]. In contrast, FFP and GR/RDF treatments showed comparatively lower yield components, largely due to asynchronous nutrient supply particularly early nitrogen stress and late-season potassium deficiency. Numerous studies have shown that potassium plays a critical role in carbohydrate transport, enzyme activation, and grain filling in rice, and its omission limits yield even under adequate nitrogen supply (Sridhara, 2008; Buresh *et al.*, 2010) [4, 36]. Thus, the superior yield attributes under NE-based SSNM provide a mechanistic explanation for the observed yield advantages.

3. Economic performance and profitability of nutrient expert®-rice



The economic analysis across locations clearly indicates that NE-based SSNM substantially improves farm profitability compared with FFP, GR, and RDF (Table 3) (Budhathoki *et al.*, 2018; Amgain *et al.*, 2021; Mannade *et al.*, 2017; Singh *et al.*, 2019; Qureshi *et al.*, 2016) [3, 21, 28, 35]. Net returns under FFP ranged from USD 700 to 1100 ha⁻¹, whereas NE-based SSNM consistently achieved higher returns (USD 1100-1450 ha⁻¹), as reported across Nepal and India (Budhathoki *et al.*, 2018; Mannade *et al.*, 2017; Singh *et al.*, 2019; Acharya *et al.*, 2022) [1, 21, 35]. The largest economic benefits were observed in regions where fertilizer use was traditionally imbalanced, such as Nepal, Bihar, and Chhattisgarh (Budhathoki *et al.*, 2018; Mannade *et al.*, 2017; Singh *et al.*, 2019) [21, 35]. Importantly, the profitability gains under NE were driven primarily by yield enhancement and improved fertilizer

efficiency rather than increased input costs (Qureshi *et al.*, 2016; Mandal *et al.*, 2016) [20, 28]. In several cases, NE-based recommendations reduced nitrogen input while increasing potassium application, leading to higher yield per unit of fertilizer applied (Mannade *et al.*, 2017; Singh *et al.*, 2019) [21, 35]. This finding supports earlier reports that SSNM-based approaches improve profitability by optimizing nutrient allocation rather than intensifying fertilizer use (Mandal *et al.*, 2016; Jat *et al.*, 2018) [18, 20].

In the Indo-Gangetic Plains (IGP), where detailed cost data were expressed as percentage gains, NE-based SSNM increased net returns by 8-12% over FFP, demonstrating that even modest yield improvements translate into meaningful income gains under large-scale cereal systems (Sapkota *et al.*, 2021) [32].

Table 3: Economic performance (net returns, USD ha⁻¹) under different nutrient management practices

Treatments	Lamjung	Jhapa-Morang	IGP	Pusa, Bihar	Chitwan	IARI	Raipur	Pantnagar
FFP	750-800	800-900	850-950	900-950	700-850	900-1000	850-900	1000-1100
GR / State rec.	850-900	950-1050	-	1000-1050	900-1000	1000-1100	950-1000	1100-1200
RDF	-	-	-	1050-1100	-	1050-1150	1000-1100	1150-1250
NE-based SSNM	1100-1200	1200-1350	+8-12%	1200-1300	1150-1250	1300-1400	1200-1300	1350-1450

Table 3: Budhathoki *et al.*, (2018); Amgain *et al.*, (2021) [3]; Sapkota *et al.*, (2021) [32]; Singh *et al.*, (2019) [35]; Acharya *et al.*, (2022) [1]; Sadhukhan *et al.*, (2023) [31]; Mannade *et al.*, (2020); Qureshi *et al.*, (2016) [28]

4. Benefit-cost ratio and economic efficiency

Table 4: Benefit-Cost (B:C) ratio under different nutrient management practices

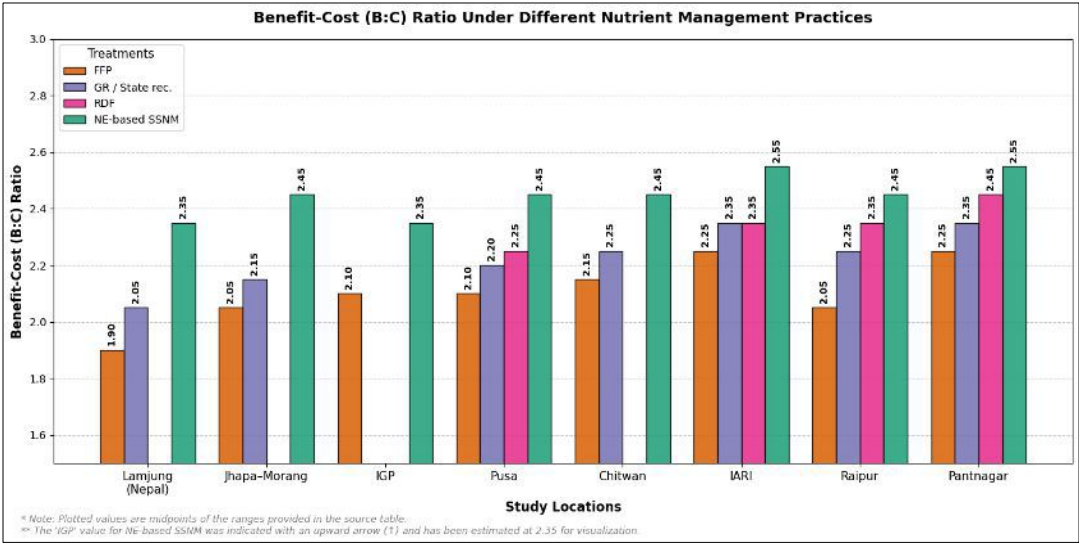
Treatments	Lamjung	Jhapa-Morang	IGP	Pusa	Chitwan	IARI	Raipur	Pantnagar
FFP	1.8-2.0	2.0-2.1	2.0-2.2	2.1	2.1-2.2	2.2-2.3	2.0-2.1	2.2-2.3
GR / State rec.	2.0-2.1	2.1-2.2	-	2.2	2.2-2.3	2.3-2.4	2.2-2.3	2.3-2.4
RDF	-	-	-	2.2-2.3	-	2.3-2.4	2.3-2.4	2.4-2.5
NE-based SSNM	2.3-2.4	2.4-2.5	↑	2.4-2.5	2.4-2.5	2.5-2.6	2.4-2.5	2.5-2.6

Table 4: Budhathoki *et al.*, (2018); Amgain *et al.*, (2021) [3]; Sapkota *et al.*, (2021) [32]; Singh *et al.*, (2019) [35]; Acharya *et al.*, (2022) [1]; Sadhukhan *et al.*, (2023) [31]; Mannade *et al.*, (2020); Qureshi *et al.*, (2016) [28]

The benefit-Cost (B:C) ratio followed trends similar to net returns (Table 4) (Budhathoki *et al.*, 2018; Mannade *et al.*, 2017; Singh *et al.*, 2019; Acharya *et al.*, 2022) [1, 21, 35]. NE-based SSNM consistently recorded the highest B: C ratios (2.3-2.6) across locations, compared with 1.8-2.3 under FFP and 2.0-2.4 under GR/RDF, as observed across Nepal and

India (Budhathoki *et al.*, 2018; Mannade *et al.*, 2017; Qureshi *et al.*, 2016; Singh *et al.*, 2019) [21, 28, 35]. Higher B:C ratios under NE indicate greater economic efficiency and reduced financial risk, which is particularly important for smallholder farmers with limited capital (Qureshi *et al.*, 2016; Mandal *et al.*, 2016) [20, 28].

Partial adoption of precision approaches (e.g., GR or RDF) improved B: C ratios compared with FFP, but these gains were consistently lower than those achieved under full NE-based SSNM (Budhathoki *et al.*, 2018; Acharya *et al.*, 2022) ^[1]. This highlights that balanced and complete implementation of SSNM principles is necessary to maximize economic benefits (Satyanarayana *et al.*, 2012; Majumdar *et al.*, 2014) ^[19, 34].



5. Optimization of fertilizer use and nutrient use efficiency

Table 5: Optimization of fertilizer use and nutrient use efficiency under NE-based SSNM (pooled synthesis)

Parameter	FFP	GR / RDF	NE-based SSNM
Nitrogen applied (kg ha ⁻¹)	130-160	120	90-120
P ₂ O ₅ applied (kg ha ⁻¹)	40-60	60	25-40
K ₂ O applied (kg ha ⁻¹)	0-20	40	50-60
N fertilizer saving (%)	-	-	15-35
Agronomic efficiency of N	Low	Moderate	High
GWP reduction (%)	-	-	2.5-49

Table 5: Budhathoki *et al.*, (2018); Amgain *et al.*, (2021) ^[3]; Sapkota *et al.*, (2021) ^[32] Singh *et al.*, (2019) ^[35] Acharya *et al.*, (2022) ^[1] Sadhukhan *et al.*, (2023) ^[31] Mannade *et al.*, (2020); Qureshi *et al.*, (2016) ^[28]

One of the most significant outcomes of NE-based SSNM is its ability to optimize fertilizer input while enhancing productivity (Table 5). Compared with FFP, NE-based SSNM reduced nitrogen application by 15-35%, while maintaining or increasing grain yield. At the same time, phosphorus application was adjusted downward where soil supply was sufficient, and potassium application was increased to correct long-term nutrient mining. This rebalancing of nutrient inputs resulted in higher agronomic efficiency of nitrogen and improved overall nutrient use efficiency. These findings align with earlier reports that SSNM can reduce nitrogen input by up to 30% without yield loss by improving synchronization between nutrient supply and crop demand (Wang *et al.*, 2007; Dobermann *et al.*, 2004) ^[9, 10, 11].

6. Environmental implications and sustainability

Beyond productivity and profitability, NE-based SSNM offers clear environmental advantages. NE-based SSNM reduced global warming potential (GWP) by 2.5-49%, primarily through reduced surplus soil nitrogen and lower nitrous oxide (N₂O) emissions. Excessive nitrogen application under FFP and blanket recommendations is a major contributor to N₂O emissions in rice systems (Xia and Yan, 2011; Chen *et al.*, 2014). Large-scale assessments suggest that widespread adoption of NE-based SSNM in rice-wheat systems could substantially reduce fertilizer consumption and greenhouse gas emissions while increasing food production (Sapkota *et al.*, 2021; Sadhukhan *et al.*, 2023) ^[31, 32]. Thus, NE-based SSNM aligns strongly with the principles of climate-smart and sustainable intensification

Table 6: Environmental performance of nutrient expert®-based ssnm across rice systems

Indicator	Farmers' practice	Government/ State recommendation	NE-based SSNM
Nitrogen application	High/ imbalanced	Moderate	Optimized (−15 to −35%)
Potassium balance	Deficient	Moderate	Balanced / corrective
N ₂ O emissions	High	Medium	Low (−2.5 to −49%)
Global warming potential (GWP)	Baseline	Slightly reduced	Significantly reduced
Yield per unit GHG	Low	Medium	High
Long-term sustainability	Poor	Moderate	High

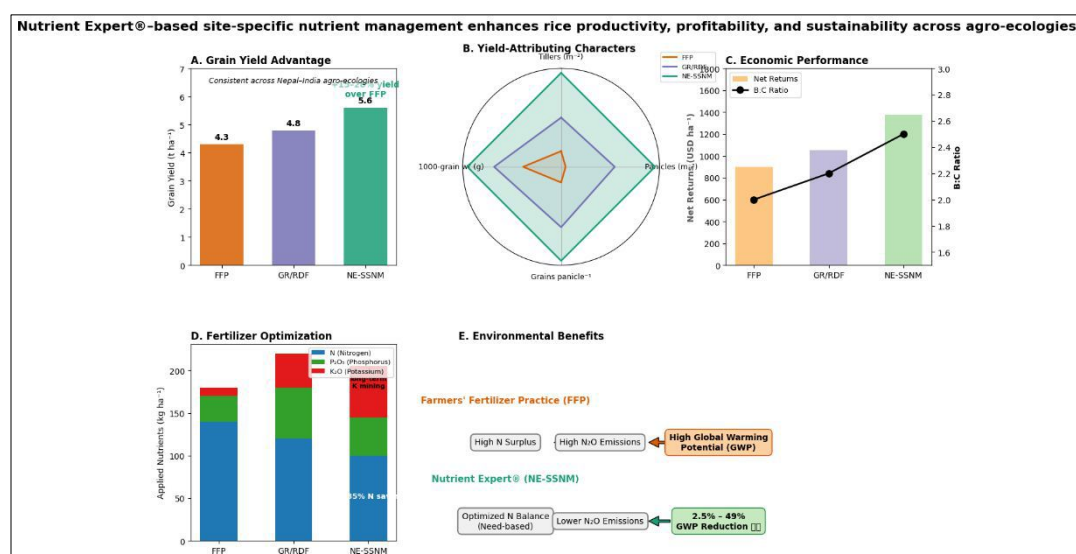
Summery

Imbalanced fertilizer use and blanket nutrient recommendations remain major constraints to sustainable rice (*Oryza sativa* L.) productivity in South Asian farming systems. Farmers' Fertilizer Practices (FFP) are often resource-driven and nutrient-biased, while government-recommended doses (GR) apply uniform rates without accounting for field-specific variability in soil fertility and yield potential. This review synthesizes multi-location, farmer-participatory trials evaluating the performance of Nutrient Expert®-Rice (NE), a decision-support tool based on site-specific nutrient management (SSNM) principles. Data were compiled from sixteen on-farm trials conducted across diverse agro-ecological regions, comparing NE with FFP and GR in terms of grain yield, profitability, and Nutrient Use Efficiency (NUE).

Across sites, NE consistently outperformed both FFP and

GR. Grain yield increased by an average of 26% over FFP and 15% over GR, with yield gains ranging from 0.8 to 2.0 t ha⁻¹. Gross margins improved by approximately 40% over FFP, with profitability increases exceeding 100% in hybrid rice systems. Enhanced economic returns were primarily driven by yield gains rather than disproportionate increases in fertilizer inputs. NE also improved NUE, particularly through optimized nitrogen splitting and correction of chronic potassium under-application, achieving NUE improvements of up to 97% in some hybrid systems.

The findings demonstrate that Nutrient Expert®-Rice effectively bridges yield gaps, enhances farm profitability, and promotes balanced fertilizer use compared with conventional fertilization approaches. Adoption of NE offers a scientifically robust and scalable pathway toward improving rice productivity while supporting economic and environmental sustainability in intensive rice-based systems.



Conclusion

Nutrient Expert®-based Site-Specific Nutrient Management (NE-SSNM) provides a scientifically robust and practical alternative to farmers' fertilizer practices and blanket government recommendations in rice systems. Across diverse agro-ecological regions, NE consistently improved grain yield, farm profitability, and nutrient use efficiency while promoting balanced fertilization. Yield gains were achieved through better synchronization of nutrient supply with crop demand, particularly optimized nitrogen splitting at critical growth stages, enabling higher productivity with more efficient fertilizer use. Unlike static recommendations, NE adjusts fertilizer rates according to field-specific conditions, correcting nutrient imbalances—especially chronic potassium under-application—and enhancing sustainable nutrient management. Importantly, increased economic returns were driven by improved input optimization rather than excessive fertilizer application, making NE both feasible and cost-effective for smallholder farmers. Wider adoption of NE-SSNM can help close yield gaps, enhance food security, and support sustainable intensification of rice and rice-wheat systems in South Asia and similar agro-ecologies worldwide.

Future line of work

Future research should emphasize multi-location and multi-season validation of Nutrient Expert®-based SSNM across diverse soils, climates, rice varieties, and cropping systems

to enhance its robustness and regional calibration. Long-term experiments are required to assess impacts on soil health, nutrient balances, and overall system sustainability. Integration of NE with soil testing, sensor-based tools (e.g., LCC, SPAD, remote sensing), weather advisories, and digital mobile platforms can further improve precision and farmer accessibility. Expanding recommendations to include secondary and micronutrients, stress-prone environments (drought, salinity, direct-seeded rice), and integrated use of organic amendments will strengthen its comprehensiveness. Additionally, socio-economic adoption studies, extension strategies, and supportive policy frameworks are essential to accelerate large-scale implementation and promote sustainable intensification of rice-based production systems.

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