Journal of Agriculture and Food Research 23 (2025) 102181

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Site-specific nutrient management for rice in Nepal: Estimating indigenous nutrient supply, improving fertilizer recommendations, and enhancing yield in the Terai Region

Santosh Marahatta [a,*], Shrawan Kumar Sah [a], Andrew McDonald [b], Jagadish Timsina [c], Rupak Karn [d], Krishna Prasad Devkota [e]

[a] *Faculty of Agriculture, Agriculture and Forest University (AFU), Rampur, Chitwan, Nepal*
[b] *International Maize and Wheat Improvement Center (CIMMYT), South Asia Regional Office, Kathmandu, Nepal*
[c] *International Fertilizer Development Centre (IFDC), Muscle Shoals, AL, USA and Institute for Study and Development Worldwide (IFSD), Sydney, Australia*
[d] *North Dakota State University, Carrington Research Extension Center, Carrington, United States of America*
[e] *International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco*

ARTICLE INFO

Keywords:
Nutrient-use efficiency
Indigenous nutrient supply
Fertilizer opotimization
Nutrient omission plots
Soil fertiity management
Sustainable rice intensification

ABSTRACT

To address declining soil fertility and stagnating rice yields in farmers' fields, this study evaluated 4-R (right-source, right-rate, right-time, right-place) principles based site-specific nutrient management (SSNM) strategies and varying potassium application rates in the western foothills of Nepal. Field experiments conducted between 2011–2013 and2022–2023 quantified the indigenous nutrient supply (INS) and evaluated the performance of SSNM strategies. These strategies incorporated real-time nitrogen management using leaf color charts (LCC), soil plant analysis development (SPAD), and Nutrient Expert (decision support tool) along with varying K rates on K-deficient soils to evaluate impacts on yield, nutrient uptake, and nutrient-use efficiencies. The results revealed significant spatial variability in soil nutrient levels, with nitrogen (N) being most limiting, followed by phosphorus (P) and K, with mean INS of 53, 29, and 84 kg N, P_2O_5, and K_2O ha^{-1}. SSNM increased rice yield by 36 % (1.68 t ha^{-1}) over traditional farmer practices and by 12 % over blanket recommendations, while reducing N and P_2O_5 inputs by 4 % and 28 %, respectively. Potassium application needed to be increased by 80 % to prevent soil depletion, indicating that the current K_2O recommendationshould be doubled to 80 kg ha^{-1} to sustain yield and nutrient uptake. LCC-based N increased yield by 4 % without additional N, while SPAD-based N application further saved 8 kg N ha^{-1}. Farmers' current practices yielded 4.69 t ha^{-1} reflecting a 33 % yield gap compared to attainable yield (7.0 t ha^{-1}). The combine use of LCC-based N with SSNM and Nutrient Expert achieved yields of 6.61 t ha^{-1}, reduced yield gap just to 5.5 %. Overall, SSNM proved to be a robust strategy for addressing nutrient deficiencies, and improving fertilizer recommendation and use effeciencies in rice, delivering agronomic, economic, and environmental benefits to smallholder systems. However, its wider adoption requires targeted farmers' training and strengthened extension support.

1. Introduction

The green revolution, which promoted the use of high-yielding varieties, increased fertilizer rates, and expanded irrigation, lead to dramatical rice yield gains in Asia during 1978–2000 [1]. Thereafter, from 2000 to 2022 , the annual yield growth was almost half of the earlier rate, i.e., 1.65 % [2,3]. This yield stagnation, particularly in rice, is closely linked to deckining soil fertility and organic matter loss, exacerbated by excessive irrigation and fertilizer useunder intensive systems [4]. Fertilizers now accounts for approximately 10–30 % of the total rice production cost in irrigated Asian farms [5,6], and the the rising prices - particularly of nitrogen - poses a direct threat to form profitability. High input costs reduce the net returns unless accompanied by yield gains, suggesting an urgent need to develop suitable nutrient management practices that not only increase rice yield but also improve the fertilizer use efficiency and maximize profitability.

This article is part of a special issue entitled: fertilizer and fertilization in crop production published in Journal of Agriculture and Food Research.

* Corresponding author.
E-mail address: smarahatta@afu.edu.np (S. Marahatta).

https://doi.org/10.1016/j.jafr.2025.102181
Received 23 March 2025; Received in revised form 9 June 2025; Accepted 13 July 2025
Available online 17 July 2025

However, farmers' decision-making in fertilizer management is influenced by multiple agronomic and socio-economic factors. In Asia, farmers' fertilizer use in rice is mostly based on blanket recommendations, often made without field evaluation and thus failing to achieve desired nutrient balances. Excessive N use during the Green Revolution period led to low N-use efficiency and environmental issues like water pollution, while other essential nutrients like phosphorus (P) and potassium (K) were under-applied [2]. Rice growers try to diversify and intensify crop sequences, planting dates, establishment methods, varieties, and residue management to suit their local conditions and specific needs as much as possible. Such diversification results in soil fertility variability spatially and temporally. Hence, the blanket fertilizer recommendations can't address the high spatial variability commonly found in smallholder farmers' fields practicing intensive farming systems [7–10]. The spatial variability in soil nutrient supply and fertilizer response is attributed to differences in inherent soil fertility [11] or management practices [10,12]. Hence, to improve rice production in intensive and diversified systems, balanced and customized fertilizer applications tailored to local physical and socio-economic conditions are essential.

Soil fertility, fertilizer application, and crop response to nutrient inputs vary across the rice fields and seasons [11,13]. Location-, soil-, and season-specific variability in indigenous nutrient supply (INS) necessitates crop demand-based nutrient recommendations to minimize nutrient loss and optimize efficiency [7]. Quantification of INS – an inherent characteristic of soil for supplying N, P, and K - is essential to quantify the site- or soil-specific nutrient needs and recommendations [11,14,15].

Site-specific nutrient management (SSNM), guided by 4-R principles (right-source, right-rate, right-time, right-place), is a low-tech, plant-based approach for optimizing the N, P, and K application to crop production [16]. It optimizes nutrient use and ensures a balanced nutrient supply by addressing spatial variability in crop fields. Crop nutrient requirements in SSNM quantify crop nutrient needs economically, measure the potential INS, estimate P and K balances to sustain soil reserves without further depletion, monitor plant N status during critical growth stages, and apply nutrients to enhance their use efficiencies [9,10]. SSNM empowers farmers to dynamically adjust fertilizer application to bridge the gap between the crop nutrient demand and nutrient supply from indigenous sources such as soil, crop residues, and manures [2,5]. The SSNM approach focuses on applying nutrients at optimal rates and times to achieve high yields, improve nutrient use efficiency, and thus is essential for long-term sustainability [9,10,15,17]. Thus, SSNM-based crop management significantly impacts the effectiveness of both inherent and applied nutrients, alongside soil variability and nutrient management practices.

Nepal's soils, predominantly Inceptisols with elevated mica and 2:1 clay mineral, were previously identified as K-sufficient [18]. Consequently, a low rate of 30 kg K_2O ha^{-1} was recommended for rice in 1976 [19]. However, with continuous practice of cereal-based cropping systems, inadequate K fertilization, complete residue removal, and the use of low-quality farmyard manure have gradually depleted soil K reserves. After nearly a century of soil test-based fertilizer recommendations, they were finally revised in 2022 based on site-specific fertilizer recommendations, and the new recommendations were included in the Department of Agriculture's Extension Guidelines in 2023 [20]. Despite the new recommended rate of 30–50 kg K_2O ha^{-1}, farmers recently used only 2 kg K_2O ha^{-1} - far below the crop requirements [20,21]. This decline, driven by mineral dissociation and negative soil K balances, has led to widespread K deficiency in field crops [18]. Provincial Soil and Fertilizer Testing Laboratories' reports suggest that in Nepal's Terai region, 31.5 % of soils analyzed were K deficient. Several other studies have also reported a declining trend in soil fertility, including reduced K concentrations in Nepalese soils [12,22]. To counteract such depletion and replenish the soil K, extra K sources need to be sought. Optimizing K fertilization through the SSNM approach is crucial for improving rice yield, enhancing nutrient-use efficiency, and ensuring long-term soil health and sustainability.

Rice-based cropping systems are the foundation of food security in the Terai and foothills of Nepal and largely in the Indo-Gangetic Plains of South Asia. However, this foundation is under threat due to the stagnating rice yields. Compared to neighboring countries such as India (4.2 t ha^{-1}), Bangladesh (4.9 t ha^{-1}), and China (7.1 t ha^{-1}), Nepal's average rice yield is significantly lower (3.7 t ha^{-1}) [3,23], and far well below the attainable yield of >8.0 t ha^{-1} [9,10,24]. Among the key factors, inappropriate and imbalanced nutrient management is recognized as main cause of low nutrient-use efficiency and low rice yield in Nepal [9,10,24,25]. The use of SSNM-based crop and nutrient management practices - including tools such as leaf colour chart (LCC), Soil Plant Analysis Development (SPAD), and Nutrient Expert recommendations,-alongside optimized K application- could play a great role in increasing nutrient-use efficiency and rice yield sustainably [10,26,27]. However, SSNM recommendations must be based on existing soil nutrient variability and INS. This study therefore aims to (i) assess the spatial variability in soil properties and crop-based estimations of supplies of N, P and K in rice fields in the western Terai region of Nepal where intensive rice-based cropping systems are practiced, (ii) develop SSNM based fertilizer recommendations including the optimum K rates for emerging K deficit soil, and (iii) evaluate the potential of SSNM to improve rice yield and nutrient-use efficiency incorporating the precision N management as compared to blanket recommendations. The region largely represents the Indo-Gangetic Plains of South Asia. Hence, we anticipate that the findings of this study would be largely applicable to the entire Indo-Gangetic Plains, though care should be taken while extrapolating results due to site or soil specificity and climate variability of agricultural regions. This study hypothesizes that SSNM can address spatial variability in soil fertility and increase nutrient-use efficiency and rice productivity in the region.

2. Materials and methods

2.1. Experimental sites

Experiments were conducted in Sunawal, a representative rice-growing area in Nepal's Nawalparasi District (27° 36′ N, 83°38′ E at an altitude of 229 m above sea level), located in the Terai plains. This region has a subtropical monsoon climate characterized by distinct wet and dry seasons, with annual rainfall ranging from 1800 to 2250 mm (80 % occurring during June–September) and temperature varying between 12 °C in winter and 38 °C in summer. The experimental sites featured sandy clay loam soils with moderate acidity. Rice-wheat cropping system is the most dominant system, where farmers traditionally grow monsoon rice in the Kharif season (June–October/November), followed by wheat in the winter season (November/December–April/May). The selected sites were quite appropriate for evaluating nutrient management strategies as they represent the common practices of conventional fertilizer use in the intensive rice-based system.

A total of seven on-farm experiments evaluating the SSNM strategies - based on 4-R (right-source, right-rate, right-time, right-place) principles - and K application rates in transplanted monsoon rice were conducted in the Kharif season (from June last week to November first week) during 2011-13 and 2022-23 across Nawalparasi district in the western Terai. SSNM strategies were also evaluated in seven experiments in 2013 and three in 2023 at the Sunawal Village to evaluate. In addition, thirty-six N, P, and K omission plot experiments were conducted across the district in 2011 and 2012 to quantify the INS from rice fields. In 2023, K application rates were also evaluated in four farms exhibiting prevalent K deficiency. Farmers were selected based on their history of good field management with rice-based cropping systems, and variability in soil characteristics with field sizes of not less than 0.5 ha. Additional criteria included their representation of various cropping patterns, soil fertility and texture variations, socioeconomic conditions (land size and agricultural inputs), and accessibility to their fields alongside their willingness to participate in experiments. At each farm, a single field (replication) was the experimental unit for all treatments. Cropping systems and crop calendars for experimental sites are presented in Supplementary Material Table S1. The soil physical properties of the experimental farmers' fields greatly varied, and soil texture ranged from sandy loam to clay/clay loam (Supplementary Material Table S2, Supplementary Material Table S13).

Total weekly rainfall and average temperatures (maximum and minimum) data throughout the crop growing periods were recorded from the agro-meteorological station of the National Wheat Research Program, Bhairahawa, Rupandehi, located near the experimental and trial sites (Fig. 1). In general, in all years, there was minimal rainfall from late June to early July, followed by increasing rainfall peaking around late July/early August, with fluctuations throughout the season. Both maximum and minimum temperatures remained relatively stable, with an average of around 30 °C, and slightly below 25 °C, respectively.

2.2. Treatments and experimental design

All on-farm trials followed a standardized experimental protocol of

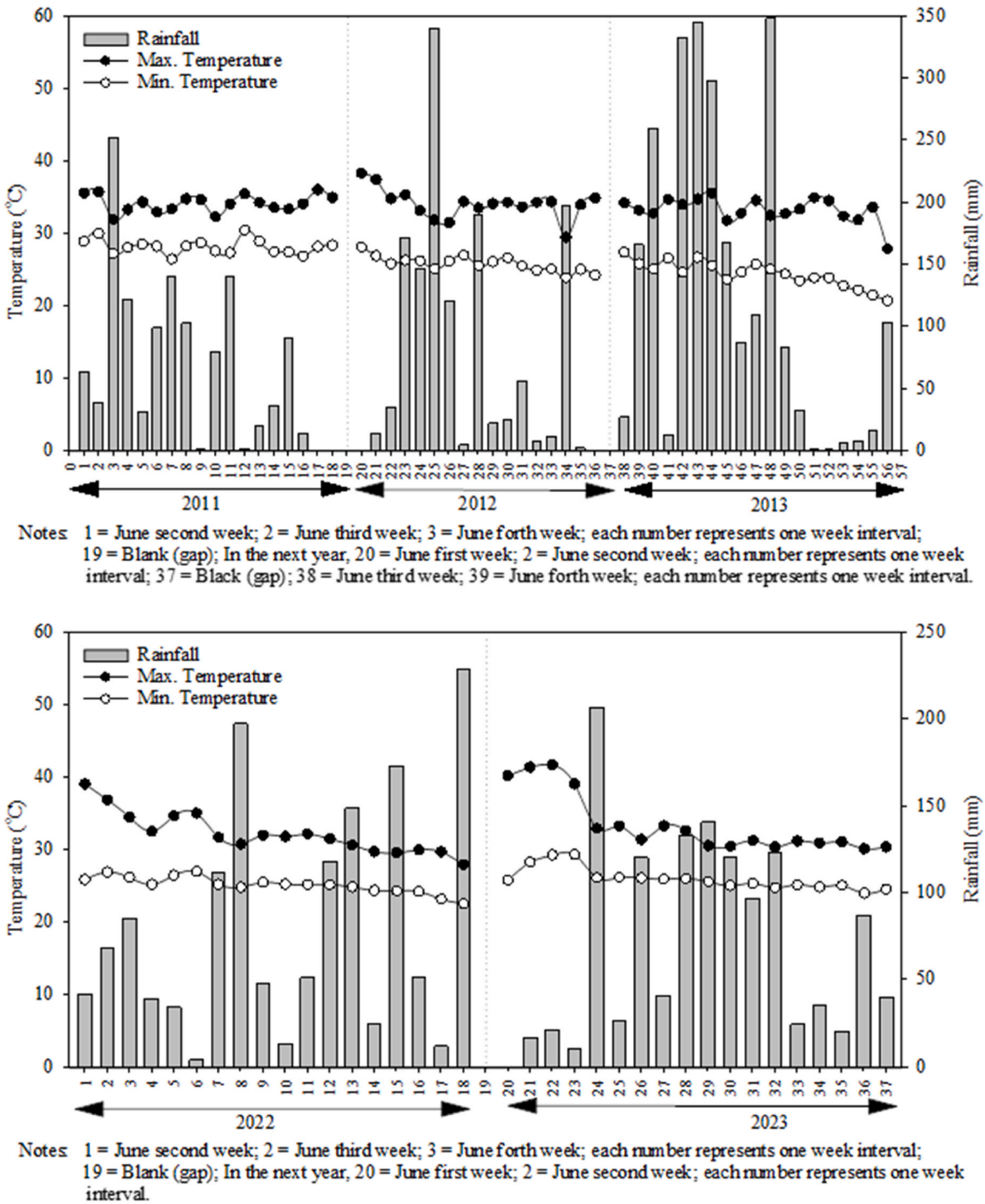

Fig. 1. Weather conditions during the rice growing seasons of 2011–2013 and 2022–2023 at Sunawal, Nawalparasi, Nepal.

the omission plot trials and SSNM experiment as described below. Based on the results of the omission plot trials and the yield target, the SSNM rates for the SSNM experiment were computed and evaluated in 2013 in seven farmers' fields and 2023 in three farmers' fields. Additionally, graduated K levels (0–160 kg K_2O ha^{-1}) were evaluated in 2022–2023 to calculate the optimal K levels.

2.2.1. Nutrient management experiments

N, P, and K omission plots: In 36 farmers' fields, 6 m × 6 m plots were maintained as N, P, and K omission plots. The N omission plot received sufficient P and K (90 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1}) to ensure only N limited yield. The P omission plot received sufficient N and K (150 kg N ha^{-1} and 60 kg K_2O ha^{-1}), and the K omission plot received sufficient N and P (150 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1}). These treatments were sampled in 2011 and 2012 to evaluate N-use efficiency and quantify the effective indigenous N supply from soil, and N supply from irrigation water, atmosphere, crop residues, and manure.

Fully fertilized plot (NPK): In the same 36 fields, a 6 m × 6 m plot was treated with high rates of N, P, and K fertilizers (150 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}) to ensure nutrients were not limiting grain yield. This treatment, tested in 2011 and 2012, was used to estimate attainable yield, and yield response by comparing it with 0-N, 0-P, and 0-K plots.

Farmers' fertilizer practice (FFP): In 2011 and 2012, in each farmer's field, one plot (treatment) was allocated representing the FFP. In 2013, this treatment was also maintained in additional seven farmers' fields. The fertilizer rate varied from farmer to farmer (Supplementary Material Table S3).

2.2.2. SSNM experiment

Site-specific nutrient management (SSNM): In each of the seven farmers' fields, a plot (6 m × 6 m) represented SSNM where nutrient applications were adjusted to field-specific conditions based on the SSNM approach (Section 2.6). This treatment was established in 2013 and 2023 to evaluate rice performance (productivity, nutrient-use efficiency, and nutrient balances) with SSNM.

Farmers' fertilizer practice (FFP): In 2013 and 2023, the FFP rates for those years were calculated based on the survey of 36 farmers during 2011 and 2012 and 25 farmers in 2022, respectively. In 2013, the nutrient rates were 53 kg N, 26 kg P_2O_5, and 8 kg K_2O ha^{-1}, whereas in 2023, the rates were adjusted to 60 kg N, 28 kg P_2O_5, and 18 kg K_2O ha^{-1}. This treatment was sampled at each site to compare with the NPK treatment in all three years to estimate yield and N-use efficiency, and the exploitable yield gap (attainable yield – yield on FFP).

Other fertility management options: Along with the SSNM and FFP treatments, other types of fertility management treatments (plot size of 6 m × 6 m) were included with minor and major variations in SSNM and FFP in seven farmers' fields in 2013 and three farmers' fields in 2023.

a. **75 % of SSNM rate:** The treatment employed 75 % of the SSNM for a 7 t ha^{-1} target yield with NPK application of 72 kg N, 32 kg P_2O_5, and 54 kg K_2O ha^{-1}.
b. **SSNM rate for P and K, LCC-based rate for N:** SSNM rate of P_2O_5 (43 kg ha^{-1}) and K_2O (72 kg ha^{-1}) was applied, while N was based on the LCC observations.
c. **Farmers' rate of N and P, recommended rate of K (only in 2013):** Farmers' rate of N (53 kg ha^{-1}) and P (26 kg ha^{-1}) was applied while the K was applied at the national recommended rate (40 kg ha^{-1}).
d. **SSNM rate for P and K, SPAD-based rate for N (only in 2023):** SSNM rate of P_2O_5 (43 kg ha^{-1}) and K_2O (72 kg ha^{-1}) was applied while N was based on the SPAD observations.
e. **Recommended rate of NPK** [28]**:** NPK rates were applied based on the national recommended rates (120 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1}).
f. **Nutrient Expert® dose (only in 2023):** NPK rates were applied based on the Nutrient Expert rice decision support tool (112 kg N, 36 kg P_2O_5, and 60 kg K_2O ha^{-1}. This is further explained in the Supplementary Materials Table S4.

In the treatment where N was managed through LCC and SPAD, one-fourth of the recommended N dose (25 kg N ha^{-1}) was applied basally along with the full dose of P and K, and N was further top-dressed based on both LCC and SPAD readings. LCC and SPAD observations were recorded from the topmost fully expanded leaves of 10 healthy rice plants per plot, beginning 14 days after transplanting and continued at 10-day intervals. For LCC, readings were taken between 8 and 10 a.m. under body shade to prevent sunlight reflection, with the LCC held horizontally and the leaf crossing vertically for accurate comparison with the six color strips. Similarly, SPAD readings were taken from the middle portion of the topmost fully expanded leaves. The average LCC and SPAD values were calculated, and N was applied @20 kg ha^{-1} whenever the reading was less than or equal to the critical value of 4 for LCC and 38 for SPAD. The actual amounts of N applied under LCC- and SPAD-based treatments are presented in Supplementary Materials Table S5.

2.2.3. Potassium levels experiment

Based on the findings from the SSNM experiment in 2013, which showed that K supplementation increased rice yield by 17 % and mitigated K depletion risks, an experiment was conducted in four farmers' fields (where soil test indicated low K levels) in 2022 and 2023 to assess the effect of five K rates (0, 40, 80, 120, and 160 kg K_2O ha^{-1}) on yield attributes, yield, and nutrient uptake. Nitrogen and P were maintained at adequate levels by applying 120 kg N and 80 kg P_2O_5 ha^{-1}. Zinc was applied at the rate of 20 kg $ZnSO_4$ ha^{-1}. Half of the total N, along with the full doses of P, Zn, and K (as per the respective treatments), were applied basally. The remaining N was applied in two equal splits at the maximum tillering and booting stages.

2.3. Agronomic management

In all experiments, a nursery bed of 250 m^2 was sown with a 100 g m^{-2} seed rate of improved rice variety Radha 4, with a 120–125-day growth duration. The nursery bed was fertilized with 100 kg N, 80 kg P_2O_5, and 80 kg K_2O ha^{-1} and frequently irrigated to aid in seedlings' recovery from drought stress. Twenty-one to twenty-five days old rice seedlings with 2–3 seedlings per hill and 20 cm × 20 cm were transplanted. Weed and pest management practices were implemented to maintain a high plant population and reduce yield losses. Management practices were carried out in collaboration with farmers, with good supervision by researchers, ensuring effective control of key production factors. The rice variety used in the experiments and trials was Radha 4, which has a light yellow colour, bold and coarse grains, high yield potential, drought tolerance, and resistance to Bacterial Leaf Blight and blast. Irrigation was done based on local practices.

Fertilizer N was applied in the treatment plots (0-P, 0-K, full NPK) as urea in three equal splits at planting, maximum tillering, and panicle initiation stages. All fertilizer P was applied as single superphosphate, and all K was applied as muriate of potash at final land preparation. Similarly, for the SSNM, 75 % of SSNM, FFP, Nutrient Expert dose, and recommended NPK, N was applied in three relatively equal splits as diammonium phosphate (DAP) and urea at planting, and as urea at maximum tillering and panicle initiation stage, while all fertilizer P and K were applied as DAP and muriate of potash at crop establishment. For SSNM – P and K, LCC/SPAD-based N application, all fertilizers P and K were applied as DAP and muriate of potash at crop establishment whereas one-fourth of recommended rate of N (30 kg ha^{-1}) was applied at crop establishment and N (as urea) was top dressed as LCC reading <4 or SPAD reading <38 with 20 kg N ha^{-1} (Supplementary Materials Table S5).

2.4. Data collection and analysis

All agronomic and soil data were collected at each farmer's field/treatment.

2.4.1. Soil analysis

A tube auger was used to collect samples at a depth of 0–20 cm to examine the physicochemical characteristics of the soil. Soil samples were air-dried before being brought to the Soil Testing Laboratory of the Soil Science Research Division, Nepal Agricultural Research Council (SSD-NARC) (https://soil.narc.gov.np/) at Khumaltar, Lalitpur. The samples were then oven-dried, ground, and sieved through a 0.5 mm wire mesh for organic matter and total N determination, and through a 2 mm sieve to determine P, K, and other soil properties. Using the potentiometric method with a 1:2 soil-to-water ratio, as Jackson [29] outlined, the pH of the soil was determined. Organic carbon content in the soil was determined with the Walkley and Black method [30]. Total N was estimated using the Kjeldahl distillation technique based on the method outlined by Bremner and Mulvaney [31]. The available P was extracted using Modified Olsen's method [32]. For K, ammonium acetate extraction (1N ammonium acetate solution) was employed, following Jackson [29]. The hydrometer method was used to determine the texture of the soil [33]. The physico-chemical properties of the soil at Sunawal, Nawalparasi, Nepal, were analyzed for three different experiments conducted in 2013, 2022, and 2023 (Supplementary Material Table S13). Soil texture ranged from loam to clay, with pH 6.31–7.56, indicating slightly acidic to neutral conditions.

2.4.2. Grain yield and yield components

Grain yield was recorded from ten 3-m-long rows in the center of the 2-m width (6 m^2) of each treatment plot, excluding the plot borders, at harvestable maturity. The harvest index was calculated using the grain yield and straw yield obtained from the same net plot. Grain yield adjusted to a standard moisture content of 14 %. Additionally, data were collected on several key parameters, including the number of effective tillers per square meter, grains per panicle, sterility percentage, and thousand-grain weight. The number of effective tillers, i.e. panicle-bearing tillers, was recorded from two 1 m^2 quadrants within each plot. To calculate the average number of grains per panicle and sterility percentage, twenty panicles were randomly selected from each plot. After threshing, the seeds were cleaned, weighed, and a sample of 250 grains was used to determine the thousand-grain weight, adjusted to a 14 % moisture content. Seed moisture content was measured using a Farmcomp Grain Moisture Tester (Wile 55).

2.4.3. Plant tissue analysis

The sampled straw and grain were used to determine the grain and straw's N, P, and K concentrations. Plant samples were dried at 65 °C for 120 h, ground to pass through a 0.5 mm sieve, and stored in brown paper bags for nutrient analysis. Plant samples were analyzed at SSD-NARC, Lalitpur. Total plant N concentration was determined using the Kjeldahl digestion method [34], plant P concentration was measured with a spectrophotometer using Olsen's method [35], and plant K concentration by a flame photometer [35]. Total plant N concentration was determined using the Kjeldahl digestion method, while plant P concentration was measured with a spectrophotometer using Olsen's method.

2.5. Relationship between grain yield in omission plots and farmers' fertility management

Yields from the 0-N, 0-P, 0-K plots and the farmers' fertility management practices were used to develop the multiple linear regression model. This analysis aimed to estimate the coefficients β_1, β_2, and β_3 that describe how strongly the grain yields from the omission plots of N, P, and K, respectively, influence the grain yield in the farmers' fertility management plots. The general form of the regression equation (1) is:

$$Y_{FFP} = \beta_0 + \beta_1 Y_{0N} + \beta_2 Y_{0P} + \beta_3 Y_{0K} + \epsilon \tag{1}$$

Where, Y_{FFP} is the grain yield in the farmers' fertility practice plots (t ha^{-1}),

Y_{0N}, Y_{0P}, and Y_{0K} are the grain yields in the nitrogen, phosphorus, and potassium omission plots (t ha^{-1}), respectively.
β_0 is the intercept,
β_1, β_2, β_3 are the regression coefficients for Y_{0N}, Y_{0P}, and Y_{0K}, and
ϵ is the error term

The regression likely used Ordinary Least Squares to minimize the sum of squared residuals (the differences between the observed and predicted values of Y_{FFP}). After running the regression, the partial correlation coefficients were calculated for each independent variable. These coefficients show the strength of the relationship between each omission plot yield (Y_{0N}, Y_{0P}, and Y_{0K}) and the farmers' plot yield (Y_{FFP}), controlling for the influence of the other variables.

2.6. Fertilizer N, P, and K rates in the SSNM treatment

Fertilizer rates for N, P, and K in the SSNM treatment were site-specific. In 2013, these rates were determined using data from nutrient omission plots and NPK plot trials conducted in the previous two years. The formula used to calculate the fertilizer rates was as follows (equation (2)):

$$FX\ (kg\ ha^{-1}) = \frac{(Nu - Ni)}{FRX} \tag{2}$$

Where, X is one of the three macro-nutrients; FX is the fertilizer nutrient requirement to achieve a specified yield target, Nu is the amount of nutrient needed to achieve target yield (kg ha^{-1}), Ni is the amount of INS (kg ha^{-1}) in the respective nutrient omission plot, and FRX is the target fertilizer recovery and assumed to be 50 % for N and K and 30 % for P [36,37]. INS was determined via N uptake in N omission plots, reflecting the integrated effects of soil, climate, and management (including pH, water regime, and establishment method).

The grain yield limited by climate and genotype is the potential yield with all other factors not limiting crop growth, but it may fluctuate among sites, farms, and years due to climate variability and weather changes [9,10,25]. The mean rice yield of the top 10 % producing farmers in nutrient sufficiency plots during 2011 and 2012 was recorded as 6.84 t ha^{-1}, thus, a target yield of 7 t ha^{-1} was set for this study. To produce 1 ton of rice, 14.7 kg N, 6.0 kg P_2O_5, and 17.4 kg K_2O are required (calculated from omission plot trials data; average yields obtained in N, P, and K omission plots were 3.63, 4.81, and 4.82 t ha^{-1} respectively, Supplementary Material Table S6 with the nutrient uptake of 53.37 kg N, 28.63 kg P_2O_5, and 84.19 kg K_2O ha^{-1} respectively, Table 4). To attain a target rice yield of 7 t ha^{-1}, the crop must absorb 103 kg of N, 42 kg of P_2O_5, and 122 kg of K_2O. In 2012, the average grain yield in N omission plots was 3.74 t ha^{-1}, indicating a soil-supplied N content of 54.99 kg ha^{-1}. Similarly, the yield in P omission plots was 4.84 t ha^{-1}, suggesting a soil-supplied P_2O_5 content of 29 kg ha^{-1}. Likewise, the yield in K omission plots was 4.94 t ha^{-1}, reflecting a soil-supplied K_2O content of 86 kg ha^{-1}. Based on these values, the SSNM recommendations in 2013 were calculated as 96 kg N, 43 kg P_2O_5, and 72 kg K_2O ha^{-1} using the above equation (2). Likewise, the SSNM rates for 2023 were also calculated.

2.7. Computation of yield gaps

The following three types of yield gaps were calculated:
Yield gap I = Attainable yield - Yield in the best treatment.
Yield gap II = Attainable yield - Yield in farmers' fertility

management.

Yield gap III = Yield in the best treatment - Yield in farmers' fertility management.

The results of 36 omission plot experiments carried out in 2011 and 2012 were used to calculate an average attainable yield for the experimental sites. From these experiments, data from the 4 best farmers' fields from optimally fertilized plots showed an average yield of 6.84 ± 0.12 t ha^{-1} (or 7 t ha^{-1}). This was considered the attainable yield.

2.8. Computation of nutrient-use efficiency

Nutrient uptake and nutrient-use efficiencies were calculated as follows:

$$\text{Nutrient uptake by grain (kg ha}^{-1}) = \frac{\%\text{ N in grain} \times \text{Grain yield}\left(\text{kg ha}^{-1}\right)}{100}$$

$$\text{Nutrient uptake by straw (kg ha}^{-1}) = \frac{\%\text{ N in straw} \times \text{Straw yield}\left(\text{kg ha}^{-1}\right)}{100}$$

Total nutrient uptake (NU) = NU in grain + NU in Straw.

Agronomic efficiency: It was calculated in units of yield increase per unit of nutrient applied, with equation (3).

$$\left(\frac{\text{Grain yield in fertilized plot}\left(\text{kg ha}^{-1}\right) - \text{Grain yield in unfertilized plot}\left(\text{kg ha}^{-1}\right)}{\text{Nutrient rate}\left(\text{kg ha}^{-1}\right)}\right) \tag{3}$$

Recovery efficiency (RE): It refers to the proportion of an applied nutrient (N, P, or K) that is taken up by a plant compared to the total amount of that nutrient applied to the soil, and was calculated with equation (4).

$$\left(\frac{\text{TNU in fertilized plot}\left(\text{kg ha}^{-1}\right) - \text{TNU in unfertilized plot}\left(\text{kg ha}^{-1}\right)}{\text{Nutrient applied in fertilized plot}\left(\text{kg ha}^{-1}\right)}\right) \tag{4}$$

2.9. Economic analysis

Cost of cultivation, gross return, net return, and benefit-cost (B:C) ratio were recorded for each treatment of the SSNM experiment in 2013 and 2023. Costs included land preparation, nursery raising, labor, fertilizers, pesticides, and harvesting, as detailed in Table SI11. Fertilizer costs varied by treatment based on nutrient management practices. Returns were calculated using the market price of harvested rice grain and straw. Net return and B:C ratio were computed by subtracting the cost of cultivation from gross returns and dividing gross returns by costs. Currency conversion from Nepalese rupees to US dollars was based on the average exchange rates in 2013 and 2023, as reported by Nepal Rastra Bank.

2.10. Statistical analysis

Dependent variables were subjected to the analysis of variance using GenStat 15th edition one one-factor randomized complete block design (http://www.vsni.co.uk/). Before analysis, data were assessed for normality and homogeneity of variance using the GVLMA (Global Validation of Linear Model Assumptions) package in R Studio. Only after confirming these assumptions, the recorded variables were analyzed using analysis of variance, and significant variables were further evaluated with Duncan's multiple range test (DMRT) for mean separation following Gomez and Gomez [38]. Treatment differences were considered statistically significant at the 0.05 level. A simple correlation and regression analysis was performed to establish relationships between different variables, SPSS v. 16 software for regression analysis, and Sigma Plot for graphical analysis. The physical maximum dose of K was obtained when the physical marginal productivity of the production factors equals 0; in other words, when the partial derivative of the production function is 0.

$$\frac{dy}{dx} = 0$$

The solution of the second-degree equation permits the establishment of the physical maximum dose of N.

$$y = a + bx - cx^2$$

$$\frac{dy}{dx} = b - 2cx$$

If x_0 is the physical maximum dose:

$$b - 2cx_0 = 0$$

Or,

$$x_0 = \frac{b}{2c}$$

3. Results

3.1. Soil physical and chemical properties across farmers' fields

Table 1 shows means and variances for physical and chemical properties of surface soil (0–20 cm) across farmers' fields. Soil pH varied from slightly acidic to slightly alkaline. Soil texture ranged from sandy loam to clay/clay loam. The soil organic carbon (SOC) and total nitrogen (TN) contents varied widely in both years. In 2011, almost all fields had low SOC and TN, while in 2012, two-thirds of farmers' fields had low SOC and TN. The available P content also varied widely, with a mean of 36 kg ha^{-1} and 38 kg ha^{-1} in 2011 and 2012, respectively. Similarly, available K content ranged from 69 to 164 kg ha^{-1} in 2011 and from 52 to 240 kg ha^{-1} in 2012.

3.2. Farmers' fertility management practices

Fertilizer management practices varied considerably across the farmers' fields, with a slight year-wise variation (Table 2; Supplementary Material Table S3). On average, about 53 kg N ha^{-1} was applied mainly through DAP during basal application and urea during top dressing. Similarly, farmers applied about 28 kg P_2O_5 ha^{-1} and about 8.5 kg ha^{-1} K_2O through DAP and MOP, respectively. Higher amounts of N were applied during basal and first top dressing (22 days after transplanting, DAT) compared to the second top dressing (36 DAT).

Table 1
Means and variances for physical and chemical analytical values for surface soil (0–20 cm) across farmers' fields of Sunawal, Nawalparasi, Nepal, 2011 and 2012.

Soil properties	2011				2012			
	Mean	SEm (±)	CV %¶	Scale	Mean	SEm (±)	CV %¶	Scale
Sand (%)	43	2.18	21	Loam	42	1.77	18	Loam
Silt (%)	34	2.04	25		24.74	2.27	40	
Clay (%)	23	1.57	28		33.26	1.85	24	
Soil pH	6.9	1.55	6.33	Medium	6.87	1.58	6	Medium
Total C (%)	0.85	0.04	20	Low	0.71	0.03	17	Low
Total N (%)	0.08	0.004	21	Low	0.095	0.005	24	Low
Available P_2O_5 (kg ha^{-1})	36	2.38	27	Medium	37.59	4.09	47	Medium
Available K_2O (kg ha^{-1})	112	9.10	33	Medium	121.68	10.99	39	Medium

Notes: ¶ CV, coefficient of variation based on field-specific average values of soil properties.

Table 2
Status and variability of farmers' soil fertility management practices in rice at Sunawal, Nawalparasi, Nepal, 2011 and 2012.

Parameters	2011				2012			
	Mean	Range	SD	CV (%)	Mean	Range	SD	CV (%)
N application (kg ha^{-1})	52	15–85	21	41	53	9–93	24	46
Basal N (kg ha^{-1})	21	0–33	8	37	22	6–44	13	60
First top dress of N (kg ha^{-1})	21	0–33	9	41	20	0–32	10	49
Time of first top dress (DAT)	21	15–29	4	18	23	17–31	4	16
Second top dress of N (kg ha^{-1})	11	0–29	11	104	11	0–36	11	99
Time of second top dress (DAT)	35.50	31.00–41.00	3.21	9.04	36.93	31.00–43.00	3.56	9.64
P_2O_5 application (kg ha^{-1})	27.60	0–45.08	10.85	39.31	25.90	0–55.20	15.21	58.73
K_2O application (kg ha^{-1})	8.23	0–34.80	11.98	145.57	8.30	0–23.00	8.05	96.99

Notes: ¶ CV, coefficient of variation based on field-specific average values; SD, standard deviation; DAT, days after transplanting.

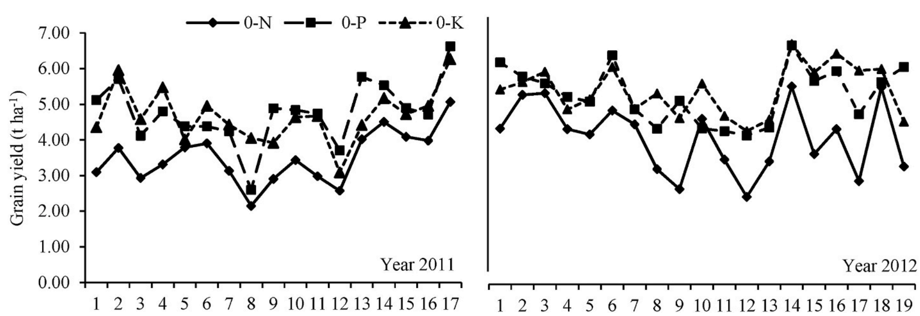

Fig. 2. Rice grain yield (t ha^{-1}) in nutrient omission plot across 17 farms in 2011 and 19 farms in 2012 at Sunawal, Nawalparasi, Nepal.

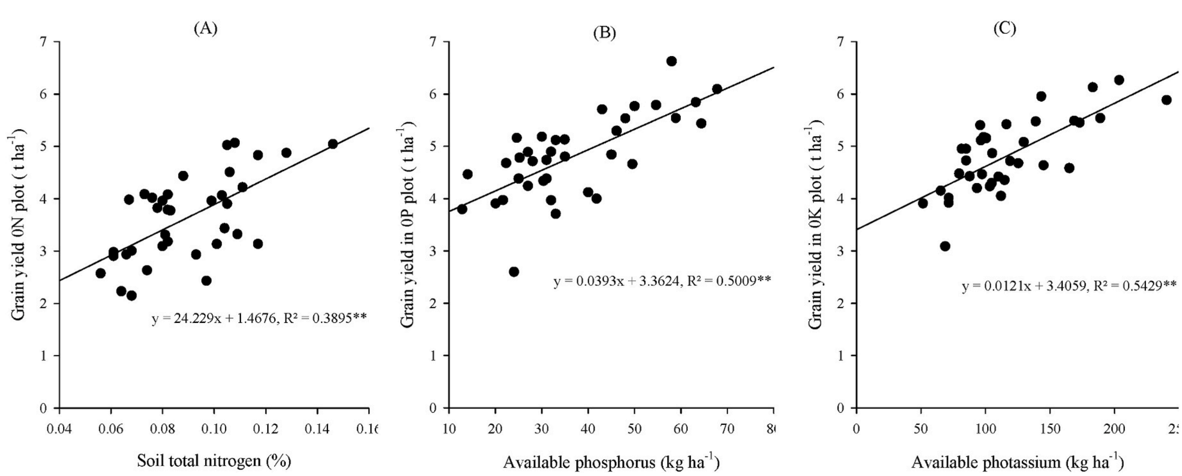

Fig. 3. Correlations between grain yield (t ha^{-1}) measured on (A) 0-N and soil total N, (B) 0-P and available P, and (C) 0-K and available K in farmers' fields at Sunawal, Nawalparasi, Nepal, 2011 and 2012.

Table 3
Means and variances for indigenous nutrient supplying (INS) capacity of rice soils at Sunawal, Nawalparasi, Nepal, 2011 and 2012.

INS capacity (ANSC) (kg ha^{-1})	Year	Mean	SD	Min	Max	CV, %
Indigenous nitrogen supply (INS)	2011 (n = 17)	51.56	10.78	31.56	74.46	20.91
	2012 (n = 19)	54.99	13.00	32.76	74.14	23.64
	Av. (n = 36)	53.37	11.96	31.56	74.46	22.41
Indigenous phosphorus supply (IPS)	2011 (n = 17)	28.41	5.35	15.48	39.48	18.83
	2012 (n = 19)	28.82	4.27	22.62	36.31	14.82
	Av. (n = 36)	28.63	4.74	15.48	39.48	16.57
Indigenous potassium supply (IKS)	2011 (n = 17)	81.85	13.37	53.93	109.44	16.33
	2012 (n = 19)	86.29	11.19	68.23	107.03	12.97
	Av. (n = 36)	84.19	12.29	53.93	109.44	14.60

Notes: CV, Coefficient of variation; SD, Standard deviation; Min, Minimum; Max, Maximum.

Significant positive quadratic associations were observed between grain yield and total N (r = 0.83**), P (r = 0.70**), and K (r = 0.58**) uptake (Data not shown). The chemical soil properties are significantly associated with grain yield in the nutrient omission plots (Fig. 3). Potassium had the strongest influence on yield (R^2 = 0.54), followed by P (R^2 = 0.51) and N (R^2 = 0.389). All three nutrients contributed significantly to yield increases, highlighting the importance of balanced and site-specific nutrient management to enhance rice yields.

3.3. Grain yield in the nutrient omission plots and variability in soil INS capacity

Mean grain yields of rice in nutrient omission plots are shown in Fig. 2 and Supplementary Material Table S6. Yield increased in the order of 0-N (3.63 t ha^{-1}) < 0-P (4.81 t ha^{-1}) ≤ 0-K (4.82 t ha^{-1}). For comparison, the average rice yield was 4.49 t ha^{-1} under farmers' management practices and 5.02 t ha^{-1} under the government-recommended practice. In contrast, the yields in the 0-P and 0-K plots were similar and substantially higher than the 0-N plots.

The INS capacity also varied among the farmers' fields and over the years (Table 3). The mean capacity to supply N, P, and K was 53, 29, and 84 kg ha^{-1}, respectively. The INS capacity varied more in the first than in the second year.

3.4. Relationships between grain yield and nutrient management treatments

Grain yields in 0-N, 0-P, and 0-K plots showed a strong correlation (data not shown). The strongest relationships were found in plots with 0N and 0P (r = 0.68**), followed by 0-N and 0-K (r = 0.67**), and 0-P and 0-K (r = 0.64**). This suggests that the interaction between N and P has a greater influence on grain yield compared to N and K, or P and K.

Grain yields in 0-N, 0-P, and 0-K plots showed strong correlations with yields in farmers' fertility management practice plots (Supplementary Material Fig. S1), where varying amounts of the three macronutrients were applied. Fertilizer rates in the FFP averaged 52, 27, and 8 kg of N, P_2O_5, and K_2O, respectively (Table 2; Supplementary Material Table S3). Of 36 farmers, only 8 % did not apply any P-containing fertilizers and 50 % did not apply any K-containing fertilizers during the experimental period (Supplementary Material Table S3). In general, grain yield was highest in farms with the high INS of all three nutrients as the correlations between grain yield obtained in FFP plots with INS (r = 0.69**), IPS (r = 0.70**), and IKS (r = 0.642**) were highly significant ($p < 0.001$). This indicates that 48 % of the variation in grain yield in the FFP plot can be explained by the yield in the 0-N plot, 49 % by the yield from the 0-P plot, and 41 % of the FFP yield variation explained by the yield in the 0-K plot; demonstrating that N and P applications influence rice yields to a greater extent compared to K.

A stepwise linear regression was performed using field-specific yield averages (2011 and 2012), resulting in the following model:

$$Y_{FFP} = 0.52 + 0.32\ Y_{0N} + 0.36\ Y_{0P} + 0.22\ Y_{0K}$$

$$R^2 = 0.59, \text{Adjusted } R^2 = 0.56, \text{SEE} = 0.53 \text{ t ha}^{-1}$$

Where, Y_{FFP} = yield (t ha^{-1}) in farmers fertility management practices,

Y_{0N} = yield (t ha^{-1}) in N omission plot, Y_{0P} = yield (t ha^{-1}) in P omission plot, Y_{0K} = yield (t ha^{-1}) in K omission plot, SEE = Standard error of the estimate.

Partial correlation coefficients in this model were 0.31 for Y_{0N}, 0.35 for Y_{0P}, and 0.22 for Y_{0K}, suggesting, that P and N are the most critical limiting factors in the current fertilizer management practices, with K playing a less dominant role even if the K application (only by 50 % of the farmers at a rate of 8 kg ha^{-1}) was very low. Across the entire range of conditions, grain yields under farmers' conventional practices were consistently higher than those in the 0-N treatment. This indicates a widespread and positive yield response to the application of nitrogen fertilizer.

Table 4
Effect of nutrient management on rice yield attributes at Sunawal, Nawalparasi, Nepal, 2013 and 2023.

Treatments	ET per square meter		Grains per panicle		Thousand grains weight (g)		Grain yield (t ha^{-1})	
	2013	2023	2013	2023	2013	2023	2013	2023
SSNM- 3 split N	277^{ab}	282^{a}	100.58	104.00	24.98^{a}	24.17	6.35^{ab}	6.38^{ab}
75 % SSNM rate	264^{ab}	252^{bc}	98.76	100.00	24.90^{a}	24.10	5.88^{bc}	6.03^{ab}
LCC-N and SSNM - P& K	280^{a}	277^{ab}	102.76	108.67	25.36^{a}	24.30	6.66^{a}	6.55^{ab}
FFP	225^{c}	237^{c}	94.94	93.67	24.26^{bc}	22.77	4.62^{d}	4.75^{c}
Rec. K and FFP N and P	252^{b}	–	99.17	–	24.04^{a}	–	5.41^{c}	–
SPAD-N and SSNM - P& K	–	284^{a}	–	104.33	–	24.93	–	6.47^{a}
Rec. NPK	270^{ab}	261^{abc}	96.98	93.33	24.83^{ab}	23.93	5.90^{bc}	5.47^{bc}
Nutrient expert	–	259^{abc}	–	105.00	–	24.23	–	6.32^{ab}
SEm (±)	8.35	8.41	3.49	3.69	0.20	0.45	0.16	0.37
LSD (=0.05)	24.45	25.93	10.08^{ns}	11.36^{ns}	0.59	1.39^{ns}	0.48	1.13
CV, %	8.30	5.50	9.34	6.30	2.18	3.30	7.50	10.6
Mean	261	265	98.87	101.29	24.73	24.06	5.80	6.03

Notes: ns, non-significant; ET, effective tillers; TGW, thousand grains weight; SSNM, site-specific nutrient management; LCC, Leaf Color Chart; SPAD, Soil Plant Analysis Development; FFP, farmers' fertility practice; Rec., Recommended. Treatment means in the column followed by the same letter(s) are not significantly different by DMRT at a 0.05 significance level.

3.5. Yield attributes, grain yield, harvest index, and economics in SSNM experiments

In the SSNM experiment in 2013, fertility management practices significantly affected the number of effective tillers per square meter, sterility percentage in both years, and thousand-grain weight, but they did not have a significant impact on the number of grains per panicle (Table 4). Combining LCC-based N with SSNM–P & K application resulted in the highest values for effective tillers (ET) per square meter, number of grains per panicle, and thousand-grain weight, along with the lowest sterility percentage. In 2023, however, combining LCC-based N application or SPAD-based N management with SSNM–P & K, and SSNM doses of nutrients resulted in higher values in these yield attributes. While yield attributes were recorded as lowest in the FFP, the resultant effect was observed on grain yield. In 2013, the application of LCC-N combined with SSNM for P and K resulted in significantly higher grain yield than all nutrient management practices and FFP except SSNM. In 2023, LCC-N or SPAD-N with SSNM-P & K, the SSNM dose and its 75 %, and Nutrient Expert-based nutrient management resulted in a statistically similar yield. Lower yield in the FFP, implying the lack of adequate nutrient input in farmers' practices. Grain yield was significantly influenced by the effective tillers per square meter, number of grains per panicle, and sterility; however, the effect of thousand grains weight was not found significant (Supplementary Material Table S8).

Significant positive correlations between grain yield and tillers per square meter (2013: r = 0.799**, 2023: r = 0.764**) and grains per panicle (2013: r = 0.532**, 2023: r = 0.637**) were observed. The sterility percentage significantly reduced (2013: r = − 0.409**, 2023: r = −0.496**) the grain yield. A significant positive correlation (2103: r = 0.464**, 2023: r = 0.689**) was also found between the harvest index and grain yield.

The costs ranged from US$ $956 to $1035 in 2013 and US$ $1101 to $1163 in 2023, with SSNM treatments generally having higher costs (Table 5; Supplementary Material Table S12). Precision approaches of nutrient management, LCC-N + SSNM (P and K) and SSNM three split application in 2013, and along with these SPAD-based N management and Nutrient Expert based recommendation exhibited the higher returns and B:C ratios (around 1.50), outperforming traditional farmer practices, which had the lowest profitability (B:C ratio of 1.15). Despite rising cultivation costs (14 % increase), these advanced methods maintained or improved profitability, indicating their economic advantage over conventional fertilizer use (Table 5).

3.6. Yield gap analysis

An average attainable yield of 7 t ha^{-1} was estimated for the experimental sites (Section 2.6). The average yield in the best treatments (LCC-N + SSNM-P & K in 2013, and LCC or SPAD - N + SSNM-P & K in 2023) were 6.66 t ha^{-1} and 6.63 t ha^{-1} respectively, resulting in a yield gap I of 0.34 t ha^{-1} and 0.37 t ha^{-1}, respectively (5 %) between the attainable and best farmer's yields (Fig. 4). The gap between the attainable yield and the average yield obtained in FFP (Yield gap II) was 2.38 t ha^{-1} (34 %) and 2.25 t ha^{-1} (32 %) in 2013 and 2023 respectively while the gap between the best treatment and farmers' practices (Yield gap III) was 2.04 t ha^{-1} (31 %) and 1.88 t ha^{-1} (28 %), respectively in 2013 and 2023.

3.7. Nutrient uptake

In the SSNM experiment in 2013, the highest nutrient uptake was recorded in LCC or SPAD-based N + SSNM-P and K treatment and nutrient expert dose. It was significantly higher than in FFP while statistically at par with the rest of the treatments (Table 6), indicating lower nutrient application. However, applying the recommended rate of K along with farmers' N and P significantly enhanced nutrient uptake compared to FFP, due to better N utilization with the higher K rate. In 2023, the recommended dose of nutrient application was poor for the N and P uptake but similar for the K uptake with the LLC or SPAD-based – N + SSNM-P and K treatment and the Nutrient Expert-based dose. A strong linear relationship was found between grain N, P, and K uptake and grain yield (r = 0.93**, 0.90**, 0.94**, respectively). Additionally, significant positive quadratic associations were observed between straw N, P, and K uptake and grain yield (r = 0.62**, 0.52**, 0.42**, respectively), as well as total N, P, and K uptake and grain yield (r = 0.86**, 0.90**, 0.51**, respectively) (Supplementary Materials Fig. S2). These relationships indicate the importance of efficient nutrient uptake for maximizing rice yield.

3.8. Yield attributes, grain yield, and harvest index in the potassium experiment

The application of K doses in the K experiment in 2023 and 2024 did not significantly influence most yield attributes of rice (Table 7). The number of ET per square meter in 2023 was significantly influenced by K, with the highest being 80 kg K_2O ha^{-1}, but statistically similar to the K_2O applications of 40 and 120 kg ha^{-1}. The cumulative effect of these yield attributes led to a significant influence on grain yield in both years. Grain yield increased significantly with K application, reaching a maximum at 120 kg K_2O ha^{-1} (5.79 t ha^{-1} in 2022, 5.70 t ha^{-1} in 2023), while the lowest yield was recorded in the control treatment (0 kg K ha^{-1}). Notably, grain yields in the range of 80–160 kg K_2O ha^{-1} were statistically similar. Straw yield was significantly affected only in the first year, with all K-treated plots showing statistically similar results (Supplementary Material Table S10). However, the harvest index

Table 5
Effect of nutrient management on cost of cultivation, return and B:C ratio of rice cultivation at Sunawal, Nawalparasi, Nepal, 2013 and 2023.

Treatments	Cost of cultivation (US $ ha^{-1})		Gross return (US $ ha^{-1})		Net return (US $ ha^{-1})		B:C ratio	
	2013	2023	2013	2023	2013	2023	2013	2023
SSNM- 3 split N	1029	1157	1553[a]	1702[a]	524[a]	545[a]	1.51[a]	1.47[a]
75 % SSNM rate	998	1129	1346[bc]	1604[a]	348[b]	476[a]	1.35[b]	1.42[a]
LCC-N and SSNM - P& K	1032	1158	1570[a]	1733[a]	538[a]	575[a]	1.52[a]	1.50[a]
FFP	956	1101	1086[d]	1274[b]	130[c]	173[b]	1.14[c]	1.16[c]
Rec. K and FFP N and P	975		1273[c]		297[b]		1.30[b]	
SPAD-N and SSNM - P& K	–	1154	–	1772[a]	–	618[a]	–	1.54[a]
Rec. NPK	1035	1163	1423[b]	1482[ab]	387[b]	319[ab]	1.37[b]	1.27[ab]
Nutrient expert	–	1151	–	1689[a]	–	538[a]	–	1.47[a]
SEm (±)			31.70	125.70	32.70	125.70	0.03	0.11
LSD (=0.05)			94.50	274.00	94.50	274.00	0.09	0.24
CV, %			6.30	9.60	23.30	33.20	6.40	9.60
Mean	1004	1145	1375	1608	371	463	1.37	1.40

Notes: ns, non-significant; ET, effective tillers; TGW, thousand grains weight; SSNM, site-specific nutrient management; LCC, Leaf Color Chart; SPAD, Soil Plant Analysis Development; FFP, farmers' fertility practice; Rec., Recommended. Treatment means in the column followed by the same letter(s) are not significantly different by DMRT at a 0.05 significance level.

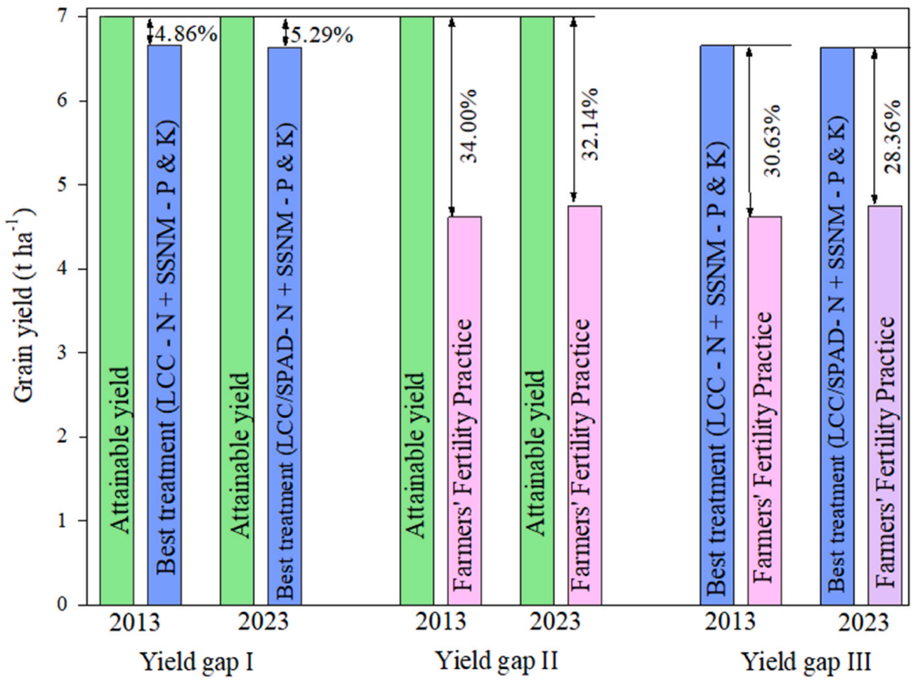

Fig. 4. Rice yield gaps under different fertility management practices at Sunawal, Nawalparasi, Nepal, 2013 and 2023.

Table 6
Effect of nutrient management on nutrient uptake in rice at Sunawal, Nawalparasi, Nepal, 2013 and 2023.

Treatments	Total nutrient uptake (kg ha^{-1})					
	Nitrogen		Phosphorus		Potassium	
	2013	2023	2013	2023	2013	2023
SSNM- 3 split N	113.62^{a}	103.90^{abc}	26.57^{ab}	20.36^{bc}	122.14^{ab}	125.65^{a}
75 % SSNM rate	101.25^{b}	98.61^{bc}	25.67^{bc}	20.56^{bc}	108.69^{b}	114.80^{a}
LCC-N and SSNM-P & K	117.28^{a}	109.26^{abc}	28.55^{a}	24.75^{ab}	130.09^{a}	120.33^{a}
FFP	74.54^{c}	77.91^{d}	20.49^{d}	18.71^{c}	74.58^{c}	89.13^{b}
Rec. K and FFP N and P	94.09^{b}	–	23.65^{c}	–	103.48^{b}	–
SPAD-N and SSNM - P& K	–	114.40^{a}	–	27.68^{a}	–	131.75^{a}
Rec. NPK	101.61^{b}	96.22^{c}	26.33^{ab}	22.89^{bc}	113.92^{ab}	112.61^{a}
Nutrient expert dose	–	111.58^{ab}	–	28.13^{a}	–	134.61^{a}
SEm (±)	3.47	4.11	0.81	1.42	6.16	7.09
LSD (=0.05)	10.03	12.66	2.33	4.37	17.78	21.84
CV, %	9.15	7.00	8.46	10.50	14.97	10.40
Mean	100.40	101.70	25.21	23.30	108.82	118.41

Notes: SSNM, site-specific nutrient management; LCC, leaf color chart; SPAD, Soil Plant Analysis Development; FFP, farmers' fertility management practice; Rec., Recommended. Treatment means in the column followed by the same letter(s) are not significantly different by DMRT at the 0.05 level of significance.

Table 7
Effect of potassium dose on yield attributes and yield of rice at Sunawal, Nawalparasi, Nepal, 2022 and 2023.

K dose (kg ha^{-1})	Effective tillers per square meter		Grains per panicle		Thousand grain weight (g)		Grain yield (t ha^{-1})	
	2022	2023	2022	2023	2022	2023	2022	2023
0	315.10^{c}	292.63	98.15	98.38	22.87	20.71	4.20^{c}	3.83^{c}
40	333.20^{ab}	308.95	104.56	105.10	23.20	22.07	4.77^{bc}	4.53^{b}
80	340.60^{a}	323.83	102.36	109.25	24.29	22.29	5.17^{ab}	5.24^{a}
120	332.28^{ab}	341.58	104.12	109.96	23.56	22.52	5.79^{a}	5.70^{a}
160	318.85^{bc}	313.44	103.41	114.32	23.24	22.78	5.50^{a}	5.46^{a}
SEm (±)	4.87	14.44	1.52	5.69	0.54	1.10	0.21	0.21
LSD (=0.05)	15.01*	44.50^{ns}	5.32^{ns}	17.52^{ns}	1.68^{ns}	3.40^{ns}	0.63**	0.64**
CV, %	3.00	9.10	3.40	10.60	4.60	10.00	8.10	8.40
Mean	328.01	316.09	102.52	107.40	23.43	22.08	5.09	4.95

Notes: ns, non-significant. Treatment means in the column followed by the same letter(s) are not significantly different by DMRT at the 0.05 level of significance.

Table 8
Effect of potassium dose on nutrient uptake and potassium use efficiency in rice at Sunawal, Nawalparasi, Nepal, 2022 and 2023.

K dose (kg ha^{-1})	Nitrogen uptake (kg ha^{-1})		Phosphorus uptake (kg ha^{-1})		Potassium uptake (kg ha^{-1})		Agronomic efficiency (kg kg^{-1} K_2O)		Recovery efficiency (%)	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
0	52.04^{d}	48.51^{c}	8.33^{b}	7.49^{c}	77.32^{d}	71.30^{b}	–	–	–	–
40	65.81^{cd}	70.51^{b}	8.81^{b}	8.10^{c}	93.09^{c}	84.77^{b}	14.18^{a}	8.19^{bc}	39.43	18.64^{b}
80	77.49^{bc}	85.96^{ab}	9.53^{b}	10.28^{bc}	105.28^{b}	105.84^{a}	12.17^{a}	13.05^{a}	34.95	35.65^{a}
120	98.37^{a}	97.05^{a}	13.16^{a}	13.89^{a}	124.45^{a}	122.54^{a}	13.21^{a}	12.51^{ab}	39.27	37.68^{a}
160	91.09^{ab}	94.10^{a}	13.00^{a}	12.66^{ab}	115.46^{a}	113.90^{a}	8.13^{b}	7.88^{c}	23.84	22.86^{b}
SEm (±)	4.52	7.00	0.90	0.97	3.21	5.70	1.23	1.24	4.90	3.08
LSD (=0.05)	13.93**	21.57**	2.78**	2.98**	9.88**	17.57**	3.94*	3.97*	5.69^{ns}	9.87**
CV, %	11.80	17.70	17.00	18.40	6.20	11.40	20.70	23.80	28.50	21.50
Mean	76.96	79.23	10.57	10.49	103.12	99.67	11.92	10.41	34.37	28.71

Notes: ns, non-significant. Treatment means in the column followed by the same letter(s) are not significantly different by DMRT at the 0.05 level of significance.

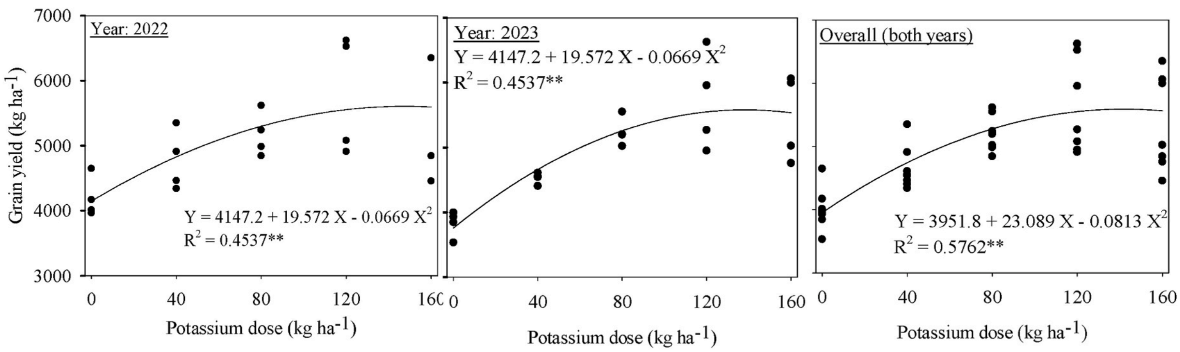

Fig. 5. Rice yield response to potassium at Sunawal, Nawalparasi, Nepal, 2022 and 2023.

remained unaffected by the K application.

N, P, and K uptake increased significantly with higher K application rates in both years, with the highest values observed at 120 kg K_2O ha^{-1} (Table 8). Control and lower dose of 40 kg K_2O ha^{-1} application resulted in a lower amount of N, P, and K uptake. Agronomic efficiency (AE) and recovery efficiency (RE) also varied with K doses, with the highest AE at 40 kg K ha^{-1} and the highest RE at 120 kg K ha^{-1}. However, AE and RE declined at the highest K dose (160 kg ha^{-1}), indicating diminishing returns.

The quadratic response of K_2O application on the grain yield of Radha-4 was significant for both years (Fig. 5). The physical maximum dose of K_2O was determined to be 142 kg K_2O ha^{-1} based on two years of data.

4. Discussions

4.1. Variability of soil properties and soil indigenous nutrient supply in the experimental sites

The physical and chemical properties of surface soil (0–20 cm) varied widely across the farmers' fields (Table 1, Supplementary Material Table S13). The observed soil texture variations, ranging from sandy loam to clay/clay loam, play a dynamic role, especially in the nutrient-holding and INS. The observed range in soil pH indicates potential challenges in nutrient availability and crop yield [39]. Low levels of SOC and total N across fields are particularly concerning, as these reflect low soil fertility status, reduced nutrient availability, and deteriorating soil health. This is also evident in the low yield observed in N omission experiments. The variabilities, as well as the low availability of available P and K, highlight that generalized approaches to soil fertility management were inadequate in the experimental sites and warrant the need for SSNM practices tailored to local soil conditions.

The study found that grain yield was significantly lower in 0-N plots, highlighting N as the most limiting nutrient in rice production in the study site. Yields in 0-P and 0-K plots were similar and higher than the 0-N plots. This is because the current soil and management conditions provided a relatively sufficient indigenous supply of P and K, and their supplementation may not have as immediate or profound an impact as N does. The significantly lower grain yield in 0-N plots is due to the low indigenous supply of N compared to its required portions of P and K. Dobermann and Cassman [40] also identified N as the primary nutrient limiting yield in many cereal crops, particularly in intensive rice systems of Asia, where high N demands are common. Phosphorus and K often have residual effects in soils, and adequate levels from previous cropping cycles or soil reserves can sustain short-term crop growth even in their [41,42]. The results of our study emphasize the need for targeted N management to optimize yield, while P and K management may be adjusted based on site-specific needs to reduce soil mining. Improved timing and rate of N application could further enhance yield potential, while P and K management should be continuously improved based on the cropping history to avoid excess applications.

The indigenous supply of N, P, and K varied across different fields and years (Table 3). The overall variability in nutrient supply, particularly for N, emphasizes the heterogeneous nature of inherent soil fertility in the study site as determined by parent materials and suggests the need for robust SSNM strategies [15]. Vanlauwe et al. [43] also noted that N dynamics are influenced by multiple factors, including SOM content, microbial activity, and environmental conditions that can lead to variable nutrient supply. Hinsinger [44] suggested that indigenous P supply and its availability are often more consistent due to its sorption characteristics and interactions with soil particles. Potassium in general is often more uniformly distributed in soils, which can be attributed to its relatively high mobility and abundance in many soils [45]. Additionally, the indigenous K supply requires careful management to prevent deficiencies, especially in cereal-based and high-yielding cropping systems with elevated K demands.

The findings of our study indicate a significant association between crop yield and soil nutrient content in omission plots (Fig. 3); however, the moderate degree of determination (38.1 % for N, 50.1 % for P, and 54.3 % for K) suggests that soil nutrient measurements alone may not sufficiently guide fertilizer recommendations for rice. Given the complexity of nutrient dynamics in rice production systems, crop-based indices of INS may play a crucial role in SSNM.

4.2. Relationship between grain yield and nutrient management practices

The significant correlations between grain yields among 0-N, 0-P, and 0-K plots indicate that the absence of any one nutrient limits the crop's ability to reach its yield potential, emphasizing the importance of balanced and optimal fertilization. The strong relationships show that the combined absence of N, P, or K has a cumulative negative impact on rice yield. The strongest correlation (Supplementary Material Fig. S3) was observed between yield from N-P omission plots, followed by N-K and P-K omission plots. The deficiency of N, P, or K, either individually or in combination, limits the crop's ability to reach its full yield potential, emphasizing the need for balanced fertilization. The interdependence between N and P in our study is evident in the high correlations between their omission plots, highlighting the need for combined application in achieving high yields. Yousaf et al. [46] found that the balanced application of N, P, and K significantly increases rice yield by 19–41 %. The slightly lower correlations between N and K, or P and K omission plots, suggest that K has a less direct influence on yield than N or P. The impact of K on rice yield is often less direct unless reserves are depleted in high-yielding systems. These findings suggest that while K is still important, N and P should be prioritized in fertility management practices to achieve optimal grain yields in the western Terai in Nepal.

Grain yields in 0-N, 0-P, and 0-K plots showed a strong correlation with yields in FFP plots (Supplementary Material Fig. S1), with N and P showing a greater influence on yield variation compared to K. These results also suggest that prioritizing N and P in fertility management practices is essential for achieving optimal grain yields, while K, though still important, has a lesser impact. This is due to that the K contents in the soils in the farmers' fields in our area were at satisfactory levels as compared to the N and P (Table 1, Supplementary Materials Table S2, Supplementary Material Table S13) This is consistent with the findings of other studies, which emphasize the essential role of N and P in promoting plant growth and grain yield, particularly in nutrient-limited soils [47]. Across the whole range, grain yield in the farmers' practice was higher than that in 0-N plots, suggesting a universal yield response to fertilizer N. Although K is important, it may not be as limiting in the experimental plots, possibly due to residual soil K levels. Nevertheless, prioritizing N, P, and K applications in fertility management practices is essential for maximizing rice yield potential.

4.3. Rice yield performance under SSNM

The findings indicate that there are significant possibilities for increasing rice production in the area, with average exploitable yield gaps in farmers' fields ranging from 0.65 to 2.38 t ha^{-1} (Table 4). This suggests that effective nutrient management could increase farmers' yields. In our study, farmers applied low amounts of N (53 kg ha^{-1} in 2013 and 60 kg ha^{-1} in 2023) and P_2O_5 (26 kg ha^{-1} in 2013 and 28 kg ha^{-1} in 2023), with insufficient amounts of K_2O (8 kg ha^{-1} in 2013 and 18 kg ha^{-1} in 2023), and only 50 % of farmers applied K. Regmi et al. [48] reported that reduced rice yields in the Terai region were due to a lack of P and K. The significantly lower yield in FFP suggests that insufficient nutrient use, particularly N, contributed to low yields in their fields. In Nepal, cereal crops are harvested close to the ground, and straw removal results in minimal K recycling, leading to very low soil K in rice fields. The yield gap between FFP and FFP-N and P + Rec. K (Table 4) could be attributed to the lack of K deficiency in farmers' fields. The blanket recommended dose yielded similar to 75 % of the SSNM rate, indicating a potential saving of nutrients (41.9 kg ha^{-1}) through balanced application. It is recommended that nutrient application practices be revised accordingly.

The SSNM approach, which is based on the 4-R (right-source, right-rate, right-time, right-place) principles, has shown promising agronomic and economic potential in closing the yield gap. Significant increases in yield attributes and nutrient uptake thus resulted in the higher grain yield over the FFP through season-specific management practices (Tables 4 and 6) due to more balanced NPK nutrition. SSNM practices involved splitting the required fertilizer N into multiple applications at critical growth stages and applying sufficient P and K fertilizers to address deficiencies. We also found that N application had the greatest partial correlation coefficient ($r = 0.65$), while poor crop management led to significantly lower yields. Further, variations in soil qualities that influenced INS, particularly N, and quality crop management were found to explain the differences in yield of SSNM treatments among the farms studied. Higher yield increments over current fertilizer management practices were also observed in other studies where the INS was low [17].

The highest yield (6.66 t ha^{-1}) obtained from the LCC-N + SSNM-P & K treatment (best treatment) was compared to the attainable yield (7 t ha^{-1}), with a yield gap I of only 0.34 t ha^{-1} (5 %), indicating the potential to further increase rice yield by further refining the SSNM rates. Alternatively, this gap could be reduced by applying nutrients for a higher yield target. The yield gap between the attainable yield and the average yield obtained in FFP (Yield gap II) was 2.38 t ha^{-1} (34 %). This wider gap reflects the inefficiencies in the current practices, likely due to low and imbalanced fertilization, and shows the great potential to increase yield by using SSNM practices. The third type of yield gap, based on the average yield obtained in the best treatment (LCC-N + SSNM - P & K) and farmers' practices (Yield gap III), resulted in a gap of 2.04 t ha^{-1}, indicating the possibility of 31 % yield increase in farmers' yield by using SSNM rates.

The yield in the Nutrient Expert based fertilizer rate, also based on 4-R (right-source, right-rate, right-time, right-place) principles, was also comparable to the SSNM, LCC, or SPAD-based N application combined with recommended P and K (Table 4). The yield achieved with the Nutrient Expert dose was comparable to that of SSNM and real-time N management using the LCC or SPAD combined with recommended P and K applications. Additionally, the yield achieved with the Nutrient Expert dose was higher than that of blanket recommendation practices. Amgain et al. [27] and Timsina et al. [49] also reported a higher yield under the Nutrient Expert dose than the government recommendation or farmers' nutrient management practices across hills and Terai regions of Nepal. Our results highlight the potential of Nutrient Expert to provide balanced nutrient management while maintaining rice yield levels, making it a practical and scalable option for farmers, especially in regions with limited access to advanced tools or soil testing facilities, and support the adoption of Nutrient Expert as a viable alternative for optimizing rice yields while ensuring efficient nutrient use. By optimizing nutrient application rates and timing, Nutrient Expert not only improves productivity but also promotes more efficient use of fertilizers compared to traditional blanket practices [10,27]. Our findings reinforce the importance of adopting precision-based nutrient management strategies such as Nutrient Expert to bridge yield gaps and enhance sustainable rice production. The findings further suggest that the Nutrient Expert based approach, which simplifies fertilizer recommendations based on crop requirements and field history, can be as effective as SSNM or LCC/SPAD-based N management.

4.4. Nitrogen uptake by rice under SSNM

The significant linear relationships (Supplementary Materials Fig. S2 and Table S9) between grain N, P, and K uptake and grain yield ($r = 0.93^{**}$, 0.90^{**}, and 0.94^{**} in 2013 and $r = 0.73^{**}$, 0.51^{**}, and 0.58^{**} in 2023) confirm that nutrient uptake is a major determinant of yield performance. The quadratic relationships observed for straw nutrient uptake indicate that while N, P, and K contribute positively to yield, excessive accumulation may not be beneficial. Thus, an over-application of nutrients without considering crop demand may result in diminishing yield gains and nutrient imbalances. These underline the need for balanced fertilization and SSNM practices, including real-time N management using LCC and Nutrient Expert, to enhance nutrient uptake and yield. Therefore, implementing balanced nutrient strategies that ensure adequate supply without over-application can enhance yields while maintaining sustainability in rice production. This has significant potential for improving rice yields in the foothills and Terai of Nepal, where yield gaps remain substantial.

Based on the average of two years, compared with farmers' fertility management practice, SSNM demonstrated 36 % and 43 % increases in yield and N uptake, whereas it was increased by 12 % and 10 %, respectively, as compared with recommended nutrient management practice (Tables 4 and 6). SSNM with LCC-based N management further improved yield and N uptake by 41 and 49 %, respectively, as compared to farmers' practices (Tables 4 and 6). The increased and balanced application rates of N, P, and K in SSNM ensured that nutrients did not limit crop growth and yield formation. The LCC reduced N requirements from 154 kg ha^{-1} to 122 kg ha^{-1}, saving 32 kg ha^{-1} (25 % of applied N) without compromising rice yields [26]. Research conducted in various regions, including India [50], Bangladesh [51], and Nepal [26], demonstrated that LCC-guided N application for different rice varieties led to higher yields compared to traditional farmer practices.

Our findings reveal that the efficiency of N applied by farmers significantly improved only when K fertilizer was also included (Tables 5 and 6). This underscores the need to address the unbalanced nutrient composition in recommended fertilizer rates to enhance nutrient use efficiency. The current negative K balance was mitigated through the application of the recommended dose of K application, leading to notable yield improvements. Addressing K imbalances with better nutrient management practices, including the recycling of crop residues, is critical for sustainable rice productivity.

We conducted the omission plot experiments during 2011 and 2012 and tested the developed SSNM dose during 2013 and 2023, likely involving different farmers and fields. Consequently, comparisons between the datasets may be influenced by different biophysical conditions (e.g., weather, soil fertility, cropping systems) and farmer practices of fertilizer application over time. Though every effort was made to maintain methodological consistency and integrity, the temporal and spatial differences may affect the comparability and generalizability of the results. Future research should aim for multi-year and multi-location trials under uniform protocols to strengthen the SSNM practices.

4.5. Effect of potassium levels on yield and nutrient uptake of rice

The application of K did not significantly affect most yield attributes, such as the number of grains per panicle and thousand-grain weight, although these parameters showed a tendency to increase with higher K doses up to 120 kg ha^{-1} (Table 7). However, the number of effective tillers per square meter was significantly influenced by K application in the first year. This aligns with previous studies indicating that potassium can promote tiller development, which is critical for achieving higher yields in rice [52]. Grain yield, a key indicator of crop productivity, responded significantly to K application in both years of the experiment (Table 7). The highest grain yield was achieved at 120 kg K_2O ha^{-1}, reaching 5.79 t ha^{-1} in 2022 and 5.70 t ha^{-1} in 2023. These results are consistent with the quadratic response observed in Fig. 5, which indicates that grain yield increased with K application up to 142 kg K_2O ha^{-1}, before plateauing, which means K application beyond this point may not provide additional yield benefits. This finding is in line with the law of diminishing returns, where incremental gains in yield decrease with higher input levels [53]. Soil K availability increases with added K fertilizer [54], but excessive K can lead to fixation [55], and due to its mobility in soil, it is prone to leaching under flooded rice cultivation [56]. This study found no yield increase beyond 120 kg K_2O ha^{-1}, suggesting no need for higher application rates. Ojha et al. [18] reported yield improvements in the Terai regions of Nepal with 50–60 kg K_2O ha^{-1}. A long-term rice-wheat experiment in Bhairahawa, Nepal, also revealed a negative annual K balance and significant K response in rice [48].

The Terai and inner Terai regions of Nepal have low availability of K due to higher cropping intensity, high rainfall intensity, and frequent leaching of K^+ [57]. Other studies have also reported that K availability in these regions is low to very low [18,48]. A low nutrient reserve was the result of continuous erosion, heavy tillage, low organic input, nutrient removal from crop harvesting, and poor crop and land management [58]. Therefore, K, an essential component of the nutrient cycle, is one of the nutrients affected by low nutrient reserves.

The uptake of N, P, and K increased significantly with higher K application rates, peaking at 120 kg K_2O ha^{-1}. This highlights the synergistic relationship between K and other essential nutrients, as adequate K availability can enhance the uptake and utilization of N and P, thereby improving overall crop productivity [59]. However, when K application exceeds crop requirements, K absorption efficiency or its use efficiency declines [60,61]. Hou et al. [62] found that higher K application in rice increased N uptake and N use efficiencies.

The potassium rates experiment was conducted exclusively in K-deficient fields, which may limit the extrapolation of results to areas with adequate or high soil K levels. The intensive rice-based systems in the Terai region of Nepal as well as in the Indo-Gangetic Plains of South Asia are becoming K-deficient, primarily due to low K application in farmers' fields through fertilizer (only 8–18 kg ha^{-1}) and limited application of organic fertilizers, which leads to K mining [63]. Additionally, residue retention is uncommon because crop residues are mostly used as livestock feed. The result of the experiment may not reflect the full range of possible outcomes under varying K fertility statuses. Therefore, future studies should consider stratified site selection across a gradient of soil K levels to better understand the crop response under diverse conditions.

5. Conclusions and future priorities

This study has demonstrated the potential of 4-R (right-source, right-rate, right-time, right-place) principles-based SSNM and Nutrient Expert, and real-time N applications using SPAD or LCC to enhance rice productivity sustainably. SSNM and Nutrient Expert based fertilizer recommendations significantly increased yields by optimizing nutrient use, reducing N and P applications and increasing their use efficiencies, and increasing K supplementation to address existing imbalances. The findings highlight N as the most limiting nutrient in the study area, followed by P and K. The INS was highly variable across fields, necessitating tailored nutrient management strategies. The use of SPAD and LCC for N application further enhanced efficiency, achieving yield gains without increasing fertilizer inputs. Potassium supplementation also emerged as critical for maintaining long-term soil fertility and preventing yield stagnation. The currently recommended K dose needs to be doubled to achieve higher yields in the K-deficient soils.

Finally, we have observed that despite the yield advantage from the SSNM- and Nutrient Expert based nutrient application, farmers in Nepal and largely in the Indo-Gangetic Plains of South Asia are not adopting SSNM in rice production. One of the major reasons is the lack of motivation among agricultural technicians and extension personnel on their SSNM. The government's agricultural agencies face a shortage of staff, which forces agricultural technicians to handle multiple responsibilities across extensive regions. While training programs and demonstration plots help introduce new technologies to farmers, the decision to adopt these practices ultimately lies with the farmers themselves. Many farmers do not have the financial capacity to buy fertilizers as needed, and those who can afford it don't have time for precision nutrient management as required for SNNM and such other tools. For the wider adoption of these tools and practices, future priorities should be towards simplifying the recommendations and integrating them into extension services. Improved farmer training, enhanced access to fertilizers, and researching and introducing better crop residue recycling practices can help adopt SSNM or Nutrient Expert practices, bridge yield gaps, and ensure sustainable intensification of rice production. The yield advantages and soil fertility improvement with SSNM and Nutrient Expert, and with the use of LCC- and SPAD-based N management, can provide scalable solutions for addressing nutrient imbalances, improving productivity, and promoting sustainable rice production in Nepal Terai and similar agroecological regions in the Indo-Gangetic Plains. To ensure their widespread adoption, targeted interventions are needed to address barriers, including financial constraints and limited technical knowledge among farmers.

CRediT authorship contribution statement

Santosh Marahatta: Writing – review & editing, Project administration, Investigation, Data curation, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Shrawan Kumar Sah:** Writing – review & editing, Methodology, Supervision, Conceptualization. **Andrew McDonald:** Supervision, Funding acquisition, Writing – review & editing, Methodology, Conceptualization. **Jagadish Timsina:** Visualization, Supervision, Methodology, Conceptualization, Writing – review & editing, Validation, Software, Funding acquisition. **Rupak Karn:** Writing – review & editing. **Krishna Prasad Devkota:** Writing – review & editing, Project administration, Funding acquisition, Supervision, Methodology, Conceptualization.

Availability of data and materials

Data will be made available upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the IFAD-funded Crop-Livestock Integration Project of CIMMYT (International Maize and Wheat Improvement Center), Kathmandu, Nepal. Nar Bahadur KC, Lokendra Khadka, and the late Anil Khadka were acknowledged for their coordination and support during the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2025.102181.

Abbreviations

Not applicable.

Data availability

Data will be made available on request.

References

[1] P. Pinstrup-Andersen, P.B.R. Hazell, The impact of the green revolution and prospects for the future, in: Reprinted from Food Reviews International, vol. 1, International Food Policy Research Institute, Washington D.C.: Massachusetts Avenue, 1985. https://pdf.usaid.gov/pdf_docs/pnaaz044.pdf.

[2] P. Chivenge, S. Zingore, K. Ezui, S. Njoroge, M. Bunquin, A. Dobermann, K. Saito, Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa, Field Crops Res. 281 (2022) 108503, https://doi.org/10.1016/j.fcr.2022.108503.

[3] FAO, FAOSTAT food balance. https://www.fao.org/faostat/en/#data/FBS, 2024.

[4] J.K. Ladha, V. Kumar, M.M. Alam, S. Sharma, M.K. Gathala, P. Chandna, Y. S. Saharawat, V. Balasubramanian, Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia, in: J.K. Ladha, Y. Singh, O. Erenstein, B. Hardy (Eds.), Integrated Crop and Resource Management in the Rice–Wheat System of South Asia, International Rice Research Institute, Los Banos, Philippines, 2009, pp. 69–108.

[5] M. Pampolino, I. Manguiat, S. Ramanathan, H. Gines, P. Tan, T. Chi, R. Rajendran, R. Buresh, Environmental impact and economic benefits of site-specific nutrient management (SSNM) in irrigated rice systems, Agric. Syst. 93 (1–3) (2007) 1–24, https://doi.org/10.1016/j.agsy.2006.04.002.

[6] A.K. Nayak, S. Mohanty, D. Chatterjee, D. Bhaduri, R. Khanam, M. Shahid, R. Tripathi, A. Kumar, S. Munda, U. Kumar, P. Bhattacharyya, B.B. Panda, H. Pathak, Nutrient management for enhancing productivity and nutrient use efficiency in rice, in: D. Mohanty, D. Chatterjee, D. Bhaduri, R. Khanam, M. Shahid, R. Tripathi, A. Kumar, S. Munda, U. Kumar, P. Bhattacharyya, B.B. Panda, H. Pathak (Eds.), Nutrient Management for Enhancing Productivity and Nutrient Use Efficiency in Rice, ICAR-National Rice Research Institute, 2018, pp. 222–239. https://krishi.icar.gov.in/jspui/bitstream/123456789/31956/1/2.1.pdf.

[7] A. Dobermann, K. G. Cassman, Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia, Plant Soil 247(1) (200)153–175. https://doi.org/10.1023/A:1021197525875.

[8] R.J. Buresh, R.L. Castillo, J.C. Dela Torre, E.V. Laureles, M.I. Samson, P.J. Sinohin, M. Guerra, Site-specific nutrient management for rice in the Philippines: calculation of field-specific fertilizer requirements by Rice Crop Manager, Field Crops Res. 239 (2019) 56–70, https://doi.org/10.1016/j.fcr.2019.05.013.

[9] J. Timsina, M.L. Jat, K. Majumdar, Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management, Plant Soil 335 (2010) 65–82, https://doi.org/10.1007/s11104-010-0418-y.

[10] J. Timsina, S. Dutta, K.P. Devkota, S. Chakraborty, R.K. Neupane, S. Bishta, L. P. Amgain, V.K. Singh, S. Islam, K. Majumdar, Improved nutrient management in cereals using Nutrient Expert and machine learning tools: productivity, profitability and nutrient use efficiency, Agric. Syst. 192 (2021) 103181, https://doi.org/10.1016/j.agsy.2021.103181.

[11] A. Dobermann, C. Witt, S. Abdulrachman, H.C. Gines, R. Nagarajan, T.T. Son, P. S. Tan, G.H. Wang, N.V.K. Chien, V.T. Thoa, C.V. Phung, P. Stalin, P. Muthukrishnan, V. Ravi, M. Babu, G.C. Simbahan, C. G, M.A.A. Adviento, Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia, Agron. J. 95 (4) (2003) 913–923, https://doi.org/10.2134/agronj2003.9130.

[12] D. Panday, R.B. Ojha, D. Chalise, S. Das, B. Twanabasu, M. Tejada Moral, Spatial variability of soil properties under different land use in the Dang district of Nepal, Cogent Food Agric. 5 (1) (2019), https://doi.org/10.1080/23311932.2019.1600460.

[13] M. Becker, R. Clavero, Z.N. Maung, O.M. Khin, S. Kong, P. Men, M.J. Regalado, S. Ro, K.K. Win, S. Pariyar, Pathways and determinants of changing nutrient management in lowland rice-based systems of Southeast Asia, Agron. Sustain. Dev. 43 (2023) 79, https://doi.org/10.1007/s13593-023-00932-6.

[14] S. Peng Cassman, D. Olk, J. Ladha, W. Reichardt, A. Dobermann, U. Singh, Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems, Field Crops Res. 56 (1–2) (1998) 7–39, https://doi.org/10.1016/S0378-4290(97)00140-8.

[15] A. Dobermann, S. Abdulrachman, H.C. Gines, R. Nagarajan, S. Satawathananont, T. T. Son, P.S. Tan, G.H. Wang, G.C. Simbahan, M.A.A. Adviento, C. Witt, Agronomic performance of site-specific nutrient management in intensive rice-cropping systems of Asia, in: A. Dobermann, C. Witt, D. Dawe (Eds.), Increasing Productivity of Intensive Rice Systems through Site-specific Nutrient Management, Science Publishers, Inc., and International Rice Research Institute, 2004, pp. 307–336, 2004.

[16] IRRI, Site-specific Nutrient Management, International Rice Research Institute (IRRI), 2006. Available on: www.irrri.org/irrc/ssnm/.

[17] A. Dobermann, C. Witt, D. Dawe, S. Abdulrachman, H. Gines, R. Nagarajan, S. Satawathananont, T. Son, P. Tan, G. Wang, N. Chien, V. Thoa, C. Phung, P. Stalin, P. Muthukrishnan, V. Ravi, M. Babu, S. Chatuporn, J. Sookthongsa, Q. Sun, R. Fu, G.C. Simbahan, M. Adviento, Site-specific nutrient management for intensive rice cropping systems in Asia, Field Crops Res. 74 (1) (2002) 37–66, https://doi.org/10.1016/S0378-4290(01)00197-6.

[18] R.B. Ojha, S. Shrestha, Y.G. Khadka, D. Panday, Potassium nutrient response in the rice-wheat cropping system in different agro-ecozones of Nepal, PLoS One 16 (3) (2021), https://doi.org/10.1371/journal.pone.0248837.

[19] D. Joshy, Soil Fertility and Fertilizer Use in Nepal, Nepal Agriculture Research Council, Khumaltar, Lalitpur, Nepal, vol. 1, 1997, p. 80.

[20] MoALD, Krishi Diary 2081, Agriculture information and training center, ministry of agriculture and livestock development (MoALD), Harharbhawan, Lilitpur, 2024. https://aitc.gov.np/uploads/documents/agriculture-diary-2081-file-2081-03-2pdf-6568-329-1719146649.pdf.

[21] S.P. Vista, S. Shrestha, N. Rawal, S. Joshi, K. Rayamajhi, S. Devkota, S. Kandel, R. Amgain, P. Paneru, S. Timilsina, Fertilizers in Nepal (NPSN: 131/078/79), National Soil Science Research Centre, Nepal Agricultural Research Council, Lalitpur, Nepal, 2022.

[22] R.M. Bajracharya, D.P. Sherchan, Fertility status and dynamics of soils in the Nepal Himalaya: a review and analysis, in: D.P. Lucero, J.E. Boggs (Eds.), Soil Fertility, 2009, 2009, pp. 111–135.

[23] MoALD, Statistical information on Nepalese agriculture 2078/79 (2021/22), Planning and Development Cooperation Coordination Division, Statistics and Analysis Section, Singhadurbar Kathmandu, 2023, pp. 1–9. https://moald.gov.np/wp-content/uploads/2023/08/Statistical-Information-on-Nepalese-Agriculture-2078-79-2021-22.pdf.
[24] K.P. Devkota, M. Devkota, G.P. Paudel, A.J. McDonald, Coupling landscape-scale diagnostics surveys, on-farm experiments, and simulation to identify entry points for sustainably closing rice yield gaps in Nepal, Agric. Syst. 192 (2021) 103182, https://doi.org/10.1016/j.agsy.2021.103182.
[25] T.J. Krupnik, J. Timsina, K.P. Devkota, B.P. Tripathi, T.B. Karki, A. Urfels, Y. K. Gaihre, D. Choudhary, A.R. Beshir, V.P. Pandey, B. Brown, H. Gartaula, S. Shahrin, Y.N. Ghimire, Agronomic, socio-economic, and environmental challenges and opportunities in Nepal's cereal-based farming systems, Adv. Agron. 170 (2021) 155–287, https://doi.org/10.1016/bs.agron.2021.06.004.
[26] S. Marahatta, Site specific nutrient management in rice, in: M.N. Paudel, D. R. Bhandari, M.P. Khanal, B.K. Joshi, P. Acharya, K.H. Ghimire (Eds.), Rice Science and Technology in Nepal, Crop Development Directorate (CDD), Hariharbhawan and Agronomy Society of Nepal (ASoN), 2017, pp. 368–375, 2017.
[27] L.P. Amgain, J. Timsina, S. Dutta, K. Majumdar, Nutrient Expert®-Rice: an alternative fertilizer recommendation strategy to improve productivity, profitability and nutrient use efficiency of rice in Nepal, J. Plant Nutr. 44 (15) (2021) 2258–2273, https://doi.org/10.1080/01904167.2021.1889590.
[28] Krishi Diary MoALD, Agriculture Information and Training Center, Ministry of Agriculture and Livestock Development (MoALD), Harharbhawan, Lilitpur, 2011.
[29] M.L. Jackson, Soil Chemical Analysis, Prentice-Hall of India Pvt. Ltd., New Delhi, 1967.
[30] A.J. Walkley, I.A. Black, Estimation of soil organic carbon by the chromic acid titration method, Soil Sci. 37 (1934) 29–38, https://doi.org/10.1097/00010694-193401000-00003.
[31] J.M. Bremner, C.S. Mulvaney, Nitrogen total, in: A.L. Page (Ed.), Methods of Soil Analysis. Agron. No. 9, Part 2: Chemical and Microbiological Properties, second ed., Am. Soc. Agron., Madison, WI, USA, 1982, pp. 595–624. https://acsess.onlinelibrary.wiley.com/doi/pdf/10.2134/agronmonogr9.2.2ed.frontmatter.
[32] S.R. Olsen, C.V. Cole, F.S. Watanabe, L.A. Dean, United States Department of Agriculture, Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate, U.S. Dept. of Agriculture, Washington, D.C., 1954.
[33] G.J. Bouyoucos, Hydrometer method improved for making particle-size analysis of soils, Agron. J. 54 (1962) 464–465, https://doi.org/10.2134/agronj1962.00021962005400050028x.
[34] D.W. Nelson, L.E. Sommers, Determination of total nitrogen in plant material, Agron. J. 65 (1973) 109–112, https://doi.org/10.2134/agronj1973.00021962006500010033x.
[35] G. Estefan, R. Sommer, J. Ryan, Methods of Soil, Plant, and Water Analysis: A Manual for the West Asia and North, Third Edition, Beirut, Lebanon: International Center for Agricultural Research in the Dry Areas, ICARDA), 2013. https://hdl.handle.net/20.500.11766/7512.
[36] S. Peng, R.J. Buresh, J. Huang, X. Zhong, Y. Zou, J. Yang, G. Wang, Y. Liu, R. Hu, Q. Tang, K. Cui, F. Zhang, A. Dobermann, Improving nitrogen fertilization in rice by site-specific N management: a review, Agron. Sustain. Dev. 30 (4) (2010) 649–656, https://doi.org/10.1051/agro/2010002.
[37] A. Dobermann, Nutrient use efficiency—measurement and management. In: fertilizer best management practices: general principles, strategy for their adoption and voluntary initiatives vs regulations, in: Proceedings of IFA International Workshop on Fertilizer Best Management Practices, 7–9 Mar 2007, Brussels, Belgium, International Fertilizer Industry Association, Paris, France, 2007, pp. 1–28. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2431&context=agronomyfacpub.
[38] K.A. Gomez, A.A. Gomez, Statistical Procedures for Agricultural Research, second ed., John Wiley & Sons, 1984. https://pdf.usaid.gov/pdf_docs/PNAAR208.pdf.
[39] N.J. Barrow, A.E. Hartemink, The effects of pH on nutrient availability depend on both soils and plants, Plant Soil 487 (1) (2023) 21–37, https://doi.org/10.1007/s11104-023-05960-5.
[40] A. Dobermann, K.G. Cassman, Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption, Sci. China Ser. C Life Sci. 48 (2) (2005) 745–758, https://doi.org/10.1007/BF03187115.
[41] A. Dobermann, T. Fairhurst, Rice: Nutrient Disorders & Nutrient Management (Handbook Series), Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), International Rice Research Institute, Philippines, 2000, pp. 1–191.
[42] N.K. Fageria, The Use of Nutrients in Crop Plants, first ed., CRC Press, 2008.
[43] B. Vanlauwe, A. Bationo, J. Chianu, K. Giller, R. Merckx, A.U. Mokwunye, O. Ohiokpehai, P. Pypers, R. Tabo, K. Shepherd, E. Smaling, P.L. Woomer, S. Ni, Integrated soil fertility management: operational definition and consequences for implementation and dissemination, Outlook Agric. 39 (1) (2010) 17–24, https://doi.org/10.5367/000000010791169998.
[44] P. Hinsinger, Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review, Plant Soil 237 (2) (2001) 173–195, https://doi.org/10.1023/A:1013351617532.
[45] P. Marschner, Z. Rengel, Nutrient Availability in Soils. Marschner's Mineral Nutrition of Higher Plants, Third Edition, 2012, pp. 315–330, https://doi.org/10.1016/B978-0-12-384905-2.00012-1.
[46] M. Yousaf, J. Li, J. Lu, T. Ren, R. Cong, S. Fahad, X. Li, Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system, Sci. Rep. 7 (2017) 1270, https://doi.org/10.1038/s41598-017-01412-0.
[47] M. Razaq, P. Zhang, H.L. Shen, Salahuddin, Influence of nitrogen and phosphorous on the growth and root morphology of Acer mono, PLoS One 12 (2) (2017) e0171321, https://doi.org/10.1371/journal.pone.0171321.
[48] A. Regmi, J. Ladha, E. Pasuquin, H. Pathak, P. Hobbs, L. Shrestha, D. Gharti, E. Duveiller, The role of potassium in sustaining yields in a long-term rice-wheat experiment in the Indo-Gangetic Plains of Nepal, Biol. Fertil. Soils 36 (3) (2002) 240–247, https://doi.org/10.1007/s00374-002-0525-x.
[49] J. Timsina, S. Dutta, K.P. Devkota, S. Chakraborty, R.K. Neupane, S. Bista, L. P. Amgain, K. Majumdar, Assessment of nutrient management in major cereals: yield prediction, energy-use efficiency, and greenhouse gas emission, Curr. Res. Environ. Sustain. 4 (2022) 100147, https://doi.org/10.1016/j.crsust.2022.100147.
[50] A.K. Shukla, J.K. Ladha, V.K. Singh, B.S. Dwivedi, V. Balasubramanian, R.K. Gupta, S.K. Sharma, Y. Singh, H. Pathak, P.S. Pandey, A.T. Padre, R.L. Yadav, Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective, Agron. J. 96 (6) (2004) 1606–1621, https://doi.org/10.2134/agronj2004.1606.
[51] M.M. Alam, J.K. Ladha, S.R. Khan, A.H. Khan, R.J. Buresh, Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh, Agron. J. 97 (3) (2005) 949–959, https://doi.org/10.2134/agronj2004.0206.
[52] A.J. Atapattu, B.D.R. Prasantha, K.S.P. Amaratunga, B. Marambe, Increased rate of potassium fertilizer at the time of heading enhances the quality of direct-seeded rice, Chem. Biol. Technol. Agric. 5 (22) (2018), https://doi.org/10.1186/s40538-018-0136-x.
[53] K. Mengel, E.A. Kirkby, H. Kosegarten, T. Appel, Potassium, in: K. Mengel, E. A. Kirkby, H. Kosegarten, T. Appel (Eds.), Principles of Plant Nutrition, Springer, Dordrecht, 2001, https://doi.org/10.1007/978-94-010-1009-2_10.
[54] G.W. Thomas, B.W. Hipp, Soil factors affecting potassium availability, in: V. J. Kilmer, S.E. Younts, N.C. Brady (Eds.), The Role of Potassium in Agriculture, 1968, pp. 269–291, https://doi.org/10.2134/1968.roleofpotassium.c13.
[55] A. Schneider, Release and fixation of potassium by a loamy soil as affected by initial water content and potassium status of soil samples, Eur. J. Soil Sci. 48 (1997) 263–271, https://doi.org/10.1111/j.1365-2389.1997.tb00374.x.
[56] A. Wakeel, H.U. Rehman, M.U. Mubarak, A.I. Dar, M. Farooq, Potash use in aerobic production system for basmati rice may expand its adaptability as an alternative to flooded rice production system, J. Soil Sci. Plant Nutr. 17 (2) (2017) 1–13, https://doi.org/10.4067/S0718-95162017005000029.
[57] S.V. Westarp, H.S. Sandra Brown, P.B. Shah, Agricultural intensification and the impacts on soil fertility in the Middle Mountains of Nepal, Can. J. Soil Sci. 84 (3) (2004) 323–332, https://doi.org/10.4141/S03-065.
[58] G. Acharya, M. McDonald, B. Tripathi, R. Gardner, K. Mawdesley, Nutrient losses from rain-fed bench terraced cultivation systems in high rainfall areas of the mid-hills of Nepal, Land Degrad. Dev. 18 (2007) 486–499, https://doi.org/10.1002/ldr.773.
[59] V. Römheld, E.A. Kirkby, Research on potassium in agriculture: needs and prospects, Plant Soil 335 (1–2) (2010) 155–180, https://doi.org/10.1007/s11104-010-0520-1.
[60] B. He, C. Xue, Z. Sun, Q. Ji, J. Wei, W. Ma, Effect of different long-term potassium dosages on crop yield and potassium use efficiency in the maize–wheat rotation system, Agronomy 12 (2022) 2565, https://doi.org/10.3390/agronomy120102565.
[61] S. Kumar, S. Dhar, A. Kumar, D. Kumar, Yield and nutrient uptake of maize (*Zea mays*)-wheat (*Triticum aestivum*) cropping system as influenced by integrated potassium management, Indian J. Agron. 60 (2016) 511–515.
[62] W. Hou, X. Xue, X. Li, M.R. Khan, J. Yan, T. Ren, R. Cong, J. Lu, Interactive effects of nitrogen and potassium on grain yield, nitrogen uptake, and nitrogen use efficiency of rice in low potassium fertility soil in China, Field Crops Res. 236 (2019) 14–23, https://doi.org/10.1016/j.fcr.2019.04.007.
[63] J. Timsina, V.K. Singh, K. Majumdar, Potassium management in rice–maize systems in South Asia, J. Plant Nutr. Soil Sci. 176 (3) (2013) 317–330, https://doi.org/10.1002/jpln.201200253.