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RESEARCH ARTICLE

Determinants of use of fertilizer best management practices: evidence from smallholder farms in Nepal

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Summary

Despite being one of the most critical agricultural inputs, chemical fertilizers are often misused by farmers in developing countries due to limited knowledge of proper nutrient management. Understanding current fertilizer application practices is essential for improving efficiency and enhancing crop productivity. This study examines the adoption and determinants of the 4R nutrient stewardship principles (also referred to as best management practices) – applying the right fertilizer source, at the right rate, at the right time, and in the right place (4Rs) – among major cereals (rice and maize) and vegetables (cauliflower) in Nepal. Using a multivariate probit model, we analysed data from 926 surveyed households across 11 districts. Our findings reveal that only 30% of farmers used the right fertilizer source supplying nitrogen (N), phosphorus (P), and potassium (K), while just 7% applied these nutrients at the right time. Additionally, 19% of farmers placed fertilizers correctly, and only 6% applied nitrogen at the right rate. Key factors influencing right nutrient management practices include gender, age, educational level of the household head, access to credit, smartphone ownership, and proximity to cooperative offices. Farmers with small landholdings, more years of farming experience, access to smartphones, and those who borrow agricultural loans are more likely to apply the right rate of nitrogenous fertilizers. The factors contributing to excessive use of nitrogenous fertilizers vary by crop type. Given the low adoption rates of 4R soil nutrient management practices, agricultural policies in Nepal should prioritize promoting these best management practices to enhance fertilizer efficiency, optimize yields, and improve long-term soil health.

Keywords: Fertilizer adoption and efficiency; 4R nutrient stewardship; Nepal; smallholder farmers; soil nutrient management

Introduction

Fertilizers play a crucial role in addressing food security, increasing agricultural productivity, and reducing rural poverty (McArthur & McCord, 2017; Stewart & Roberts, 2012). To promote fertilizer use and enhance crop yields, many developing countries have implemented fertilizer support programmes (Bruinsma, 2003; Pingali, 2012; M. Sutton *et al.*, 2013). Fertilizer subsidies constitute a significant portion of agricultural budgets in developing countries.[1] Given the significant economic costs associated with these subsidies, it is essential to promote best nutrient

[1]The fertilizer subsidy programmes constituted 24% of the agricultural budget in Malawi in 2018 (Ministry of Agriculture, 2021) and about 19% of the total public spending in Rwanda in 2022 (MINAGRI, 2022). In Nepal, the fertilizer subsidies account for approximately 30% of the agricultural budget (MoF, 2021).

management practices to improve fertilizer efficiency and maximize agricultural benefits (Kishore *et al.*, 2021; Timsina *et al.*, 2021).

One of the key pillars of agricultural sustainability is the judicious use of inputs in crop production (Cui *et al.*, 2018; Zhang *et al.*, 2015). However, farmers in developing countries often apply fertilizers based on availability and affordability rather than scientifically recommended doses and plant nutrient demands (Bora, 2022; Kishore *et al.*, 2021). Research indicates that Nepalese farmers do not consistently practice a balanced application of nitrogen (N), phosphorus (P), and potassium (K) for cereal crops (N. R. Pandit, Gaihre, Choudhary, *et al.*, 2022) or vegetables such as cauliflower (N. R. Pandit, Gaihre, Gautam, *et al.*, 2022). Inefficient nutrient application—whether through imbalanced quantities, improper placement, or incorrect timing—reduces plant nutrient uptake and lowers crop productivity and profitability (Johnston & Bruulsema, 2014).

Due to the government's heavy subsidies (65–70%) on urea (46% nitrogen content) compared to 25–30% subsidies for diammonium phosphate (DAP, 18% nitrogen content) and 30–32% subsidies for muriate of potash (MOP, no nitrogen content) (MOAD, 2022), farmers are more likely to apply excessive urea fertilizers leading to overuse of nitrogen. Several studies indicated that excessive nitrogen use has significant environmental consequences (Zhen *et al.*, 2006; Sheahan and Barrett, 2017; Wu *et al.*, 2018; Ren *et al.*, 2021), threatens agricultural sustainability (Lu & Tian, 2017; M. A. Sutton *et al.*, 2008), and poses risks to human health (Erisman *et al.*, 2013; Gourevitch *et al.*, 2018; Wang & Lu, 2020; Wangunci & Zhao, 2019). Overuse often results in diminishing returns; plants cannot absorb the excess nitrogen, leading to wasted inputs and reduced cost-effectiveness. Over time, excessive nitrogen use can degrade soil health, leading to lower productivity and the need for more inputs to maintain yields (Zhang *et al.*, 2015).

Nepal's agricultural policy emphasizes the importance of efficient fertilizer use to drive agricultural growth and productivity (ADS, 2015; APP, 1995). The Agriculture Development Strategy (ADS)—Nepal's guiding policy document—identifies poor knowledge of fertilizer best practices as a key constraint to productivity and calls for the promotion of efficient fertilizer management. A widely recognized approach to optimizing fertilizer use is the 4R nutrient stewardship framework, which advocates applying the right source of nutrients, at the right rate, at the right time, and in the right place. Developed by the International Plant Nutrition Institute (IPNI) with global partners, the 4Rs are now widely adopted as a best-practice standard for optimizing fertilizer use efficiency and minimizing environmental impacts (Johnston & Bruulsema, 2014; Bruulsema et al. 2016; Jones, 2021; Mikkelsen *et al.*, 2009; Santos, 2011; Stewart *et al.*, 2009) and can narrow the existing yield gap in agriculture (Mueller *et al.*, 2012).

In Nepal, limited research has been conducted on assessing fertilizer application practices among farmers and the nitrogen use efficiency of crops (Dhakal *et al.*, 2021; N. R. Pandit, Choudhary, *et al.*, 2022; Timilsina *et al.*, 2023). To the best of our knowledge, we are not aware of any studies that assess the determinants of 4R soil nutrient management adoption and excessive use of N fertilizers in Nepal. This study seeks to address this gap by examining the factors influencing the determinants of 4R soil nutrient management adoption and excessive N use focusing on rice, maize, and cauliflower among Nepalese farmers.[2]

[2]Rice is Nepal's most important cereal crop, accounting for 42% of the total cereal cultivation area and 48% of cereal production, followed by maize at 28% of the cultivated area and 29% of cereal production (MOAD, 2022). Among vegetables, cauliflower is the most widely grown, occupying 14% of the cultivated area and contributing 15% of vegetable production in Nepal (MOAD, 2022).

Table 1. Crops targeted, study district, and sample size

	Survey year 2021			Survey year 2022		
District name	Rice	Maize	Cauliflower	Rice	Maize	Cauliflower
Arghakhanchi	–	21	–	–		–
Baitadi	–	–	–	55	25	–
Banke	–	–	–	50	25	–
Bardiya	55	–	21	–	–	17
Dang	–	29	–	–	25	–
Doti	–	20	–	–	26	–
Kabhrepalanchok	22	25	–	60	–	20
Nuwakot	–	–	20	–	–	22
Kailali	70	–	–	45	–	–
Kanchanpur	25	–	–	20	–	–
Kapilbastu	29	30	–	30	29	–
Palpa	–	20	19	–	–	–
Salyan	–	–	–	–	30	21
Surkhet	–	–	20	–	–	–
Total	201	145	80	260	160	80

Material and methods

Data

We conducted a cross-sectional Beneficiary-Based Survey (BBS) across 14 districts in Nepal, following the methodologies outlined in the *Sampling Guide for Beneficiary-Based Surveys for Selected Feed the Future Agricultural Annual Monitoring Indicators* (Stukel & Friedman, 2016). The survey was part of the Nepal Seed and Fertilizer (NSAF) project, implemented by the International Maize and Wheat Improvement Center (CIMMYT).

The project was implemented between 2016 and 2024, during which annual surveys were conducted with beneficiary farmers. However, only the 2021 and 2022 survey rounds included questions related to the use of 4Rs nutrient management. These two rounds were used in this study, but these are not the baseline and endline surveys. As part of the project, selected farmers received training on fertilizer best management practices. About 926 farmers were selected for survey in 2021 (426) and 2022 (500) of which 63% were from Terai and 37% from hilly region. We focus only on rice, maize, and cauliflower, identified as Nepal's most significant crops (Table 1).

The survey employed a two-stage cluster sampling design to ensure representativeness. In the first stage, farmer groups served by the project at the village or community level—hereafter referred to as *clusters*—were identified across four provinces (Sudurpaschim, Gandaki, Lumbini, and Bagmati), spanning both hill (sub-tropical) and Terai (tropical) ecological regions. Roughly 100 such groups cultivating six key crops (rice, maize, lentil, onion, cauliflower, and tomato) were listed. From this pool, 30 to 32 sampling units were randomly chosen according to crop suitability within each province and ecological region.

The second stage focused on household selection. For each sampled group, a list of project beneficiaries was compiled, from which 20 to 30 households were randomly drawn using a random number generator. Trained enumerators then conducted face-to-face interviews with the selected households using Open Data Kit (ODK) software. A carefully designed and pretested questionnaire captured information on socio-economic and agricultural characteristics, food consumption, access to credit, and 4R nutrient management practices.[3]

[3]The study focuses on determinants of 4Rs nutrient use and not on the food consumption. The questionnaire can be available upon the request to authors.

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Empirical model

Multivariate probit (MVP) model to assess factors influencing 4R fertilizer usage

To analyse the determinants of 4R fertilizer use, we employed a multivariate probit (MVP) model. The 4R nutrient management practices—right source, right time, right dose, and right placement—as promoted by the project, are outlined in Table 2. Based on these guidelines, we created four binary dependent variables, each representing adherence to one of the 4R principles.

The best nutrient management practice, recommended by the Nepal Agricultural Research Council, defines right fertilizer application techniques. Farmers following the guidelines in Table 2 were considered to be using the 'right' technique. Conversely, deviations from these recommendations were categorized as 'wrong' techniques. For instance, if farmers applied only urea and DAP but excluded MOP, the crop lacked the essential potassium nutrient, resulting in unbalanced nutrition—constituting an incorrect practice. For maize cultivation, urea should be applied at the 6-leaf stage with a second top dressing at the 10-leaf stage. Moreover, if urea was applied only as basal dose during planting, it was classified as a 'wrong' technique.[4] The modelling approach enables understanding of the factors driving or hindering the adoption of proper 4R practices and informs targeted interventions for improved nutrient management.

Some farmers may apply fertilizers at the right rate and in the right place but may fail to apply them at the right time or may use only N while neglecting P and K. These decisions are often influenced by factors such as the timely availability of fertilizers and the farmers' knowledge of proper fertilizer use. Consequently, the adoption decisions across the four components of the 4R nutrient management framework are likely to be correlated.

While univariate logit or probit models can be used to analyse the adoption of each individual 'R', these methods may yield biased and inefficient estimates due to potential interdependencies among the adoption decisions. To address this issue, we employed the MVP model, which accounts for the correlations among multiple decisions and provides more accurate estimates with correct standard errors. The MVP model accommodates error correlations across equations and controls for unobserved heterogeneity (Cappellari & Jenkins, 2003). The MPV model is specified as follows:

$$T_{ih} = \alpha_i + \beta_i\, R_{ih} + \ \delta_i\, M_{ih} + \ \mu_i H_{ih} + \theta_i A_{ih} + \varepsilon_{ih} \tag{1}$$

where T_{ih} is a binary indicator of adoption for the 4R practice i by household h (where $i = 1,2,3,4$ for each of the 4Rs), R_{ih} is a binary indicator for rice growers, M_{ih} is a binary indicator for maize growers (cauliflower growers serve as the reference category,) H_{ih} are the vector of socio-economic characteristics, A_{ih} are the vector of agricultural characteristics, and ε_{ih} is the error term capturing unobserved factors.

The agricultural characteristics included in the model are total farmed area, livestock index, access to irrigation facilities, engagement in contract farming, participation in fertilizer demonstration programmes, and time to reach nearest cooperative and agrovets. The socio-economic characteristics incorporated into the model are gender of the household head, age of the household head, education level, family size, migration status, ethnicity, access to credit, smartphone ownership, household income, and affiliation with cooperatives. These variables were selected based on insights from prior studies (Mariano, Villano and Fleming, 2012; Ghimire, Huang and Shrestha, 2015; Kumar *et al.*, 2020; Aryal, Rahut, *et al.*, 2021; Aryal, Sapkota, *et al.*, 2021).

[4]While this study focuses on chemical fertilizers, it is important to acknowledge the role of organic fertilizers (e.g., farmyard manure and compost) and green manuring in nutrient management (Khanal *et al.*, 2024). Due to data limitations, precise quantities of organic inputs were not included in the quantitative analysis; however, the livestock index was used as a proxy for organic fertilizer availability. The potential impact of organic fertilizers on nutrient efficiency and soil health is discussed in the limitations and future research sections.

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Table 2. 4R nutrient management practices promoted by the Nepal Seed and Fertilizer project

Crop	Right source	Right time	Right place	Right rate
Rice	Applied Urea, DAP, and MOP	Applied DAP and MOP as basal dose and applied urea as a top dressing	Broadcasted – applied uniformly in the field	If DAP is applied 2.1 kg per katha, MOP is applied 1.7 kg per katha, and urea is applied 6.4 kg per katha (applied twice as top dressing)
Maize	Applied Urea, DAP, and MOP	Applied DAP and MOP as basal dose and applied urea as a top dressing (first top dressing at the stage of 6 leaves and second top dressing at the stage of 10 leaves)	Fertilizer is placed 5–6 cm far from the seed/plant and at the depth of 5–7 cm	If DAP is applied 4.33 kg per katha, MOP is applied 2.2 kg per katha, and urea is applied 7 kg per katha (applied twice as top dressing)
Cauliflower	Applied Urea, DAP, and MOP	At the time of transplanting seedling, apply DAP and potash, and apply urea twice as topdressing (after 30 days of seedling transplanting and at the time of crown formation)	Fertilizer is placed 5–6 cm far from the seed/plant and at the depth of 5–7 cm	If DAP is applied 8.67 kg per katha, MOP is applied 5.53 kg per katha, and urea is applied 11 kg per katha (applied twice as top dressing)

Source: Nepal Agriculture Research Council; 30 katha = 1 hectare, DAP = diammonium phosphate, MOP = muriate of potash.

In equation 1, α_i, β_i, δ_i , μ_i, θ_i are the model parameters representing the effects of explanatory variables on the adoption decision. The error terms $(\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4)$ are assumed to follow a multivariate normal distribution with a zero conditional mean and variance normalized to 1, that is, $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4 \overset{MVN}{\rightarrow} (0, \omega)$. The variance–covariance matrix (ω) is given by:

$$\omega = \begin{bmatrix} 1 & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & 1 & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & 1 & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & 1 \end{bmatrix} \tag{2}$$

where rho $\left(\rho_{ij}\right)$ is the correlation coefficient between the error terms of 4R adoption decision i and j. For the MVP model to be valid, the off-diagonal correlation terms (ρ_{ij}) should be non-zero, indicating interdependencies between the adoption decisions. We tested this using a likelihood ratio (LR) test, which evaluates whether the covariances across the equations are statistically significant. The null hypothesis assumes no correlation between the error terms $(\rho_{21} = \rho_{31} = \rho_{41} = \rho_{32} = \rho_{42} = \rho_{43} = 0)$. Rejecting this hypothesis supports the use of the MVP model, confirming that the farmers' choices regarding the adoption of different 4R practices are interrelated.

Assessing factors influencing excessive nitrogen use through a binary probit model

We employed a binary probit model to examine the factors driving excessive nitrogen use in rice, maize, and cauliflower cultivation. To construct the variable representing excessive nitrogen application, we calculated the total nitrogen from urea and DAP, using their standard nutrient compositions of 46% N and 18% N, respectively. We then measured the deviation from the recommended nitrogen application rate for each household. Households applying nitrogen at a rate exceeding a 10% deviation from the recommended dose were classified as overusers. This 10% threshold was chosen under the assumption that such an excess could negatively impact crop growth and development.

While we recognize that fertilizer recommendations can vary based on soil fertility conditions, the lack of plot-level data and information on prior soil fertility constrained our ability to adjust for these factors. Given that N requirements differ by crop, we developed separate binary indicators for overapplication in rice, maize, and cauliflower. For instance, the variable 'overuse of N for rice' equals 1 if the nitrogen application exceeds the 10% deviation threshold and 0 otherwise. To account for crop-specific factors, we estimated a separate binary probit model for each crop using the following specification:

$$N_{ch} = \alpha_c + \beta_c H_{ch} + \theta_c A_{ch} + \gamma_c E_{ch} + \delta_c Y_{ch} + \varepsilon_{ch} \tag{3}$$

where N_{ch} is a binary indicator (1= overuse of nitrogen, 0 = otherwise) for crop c in household h. Crop type includes rice $(c = 1)$, maize $(c = 2)$, and cauliflower $(c = 3)$. H_{ch} represents the household socio-economic characteristics (e.g., family size, household income, age, and education level), A_{ch} captures agricultural characteristics (e.g., total cultivated land, livestock index, and involvement in contract farming), E_{ch} is a dummy variable for the ecological zone, Y_{ch} is a dummy variable for the surveyed year, and ε_{ch} is the error term, assumed to follow a normal distribution. Parameters $\alpha_c, \beta_c, \delta_c, \gamma_c$, and θ_c are estimated for each crop. The analysis was conducted using Stata 17 statistical software. This modelling approach allows for a nuanced understanding of the socio-economic, agricultural, and ecological factors contributing to excessive nitrogen use, tailored to each crop type.

Results

This section presents descriptive and empirical results, organized into distinct subsections for clarity.

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Descriptive results

Table 3 summarizes the key statistics (mean and standard deviation) of the variables used in the analysis, categorized by crop type. The final column provides detailed descriptions of each variable. For binary (dummy) variables coded as 1 (Yes) or 0 (No), the mean represents the proportion of farmers exhibiting a specific characteristic or condition, which can be interpreted as a percentage.

Fertilizer application varied notably across crop types. All sampled rice farmers (100%) applied urea, while 97% used DAP. In contrast, 59% of cauliflower farmers used MOP. Specific adherence to the '4R' principles of nutrient management also varied by crop. About 56% of cauliflower farmers applied the right fertilizer source. Only 12% of maize farmers applied nitrogenous fertilizers at the recommended dose. About 10% of farmers applied fertilizers at the right time, and 30% ensured placement in the right location for rice cultivation. About 8% of the sampled rice farmers, 40% of the maize farmers, and 81% of the cauliflower farmers have applied excessive nitrogenous fertilizers.

The socio-economic profiles of farmers varied based on the crops they cultivated. Among three crops, higher proportion of cauliflower growers were female-headed (32%) and had a greater average number of years of education (5.59 years). A notable proportion of maize growing HHs belonged to the Dalit caste (16%) and were affiliated with cooperatives (97%). A larger share of rice growing households (HHs) had access to credit facilities (22%).

Agricultural practices also differed significantly among crop growers. A larger proportion (65%) of maize growing HHs cultivated hybrid varieties, maintained higher livestock holdings (as indicated by the livestock index), and participated in contract farming (7%) in comparison to rice and cauliflower growing households. A greater share of rice farmers had access to irrigation facilities (29%) and cultivated larger-than-average farm area (0.56 hectares). These descriptive results highlight the diversity in fertilizer use, socio-economic conditions, and agricultural practices among smallholder farmers, which are likely to influence nitrogen management decisions across different crops.

Empirical results

Factors influencing the adoption of 4R nutrient management technology

The suitability of the MVP model was first evaluated. Pairwise correlation coefficients among the residuals of the MVP model revealed statistically significant correlations for most 4R practices (Table 4), indicating interdependence among farmers' decisions regarding different 4R practices. The LR test further confirmed this, rejecting the null hypothesis of no correlation among the error terms ($\chi 2$ (df $= 6) = 481.20$, $p < 0.01$). These results validate the use of the MVP model, suggesting that farmers view the 4R practices as complimentary rather than substitutive (Table 4).

Table 5 presents the empirical results of the MVP model. The model is statistically significant based on the Wald chi-square test ($p = 0.00$), and key factors influencing 4R adoption were identified. Female-headed HHs exhibit a higher probability of adopting the right source and right placement of fertilizers. Households with higher education have higher probability of adopting right source, right time, or right placement of fertilizers. The age of the household head is positively and significantly associated with the adoption of 4R practices. Adoption behaviours differ by ethnic group. HHs from Dalit communities (historically marginalized groups) are less likely to apply fertilizers at the right rate compared to households from other ethnic backgrounds.[5]

A negative relationship was found between farm size and 4R adoption. Households with smaller landholdings are more inclined to use 4R practices. Households with credit access are

[5]Dalits in Nepal face discrimination despite legal protections. Historically marginalized under the caste system, Dalits experience social exclusion, economic disparities, and limited access to education, healthcare, and political representation (Geiser, 2005).

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Table 3. Descriptive statistics (mean) of the variables used in the analysis

Variables	Rice	Maize	Cauliflower	Overall	Variable description
Dependent variables					
Use urea (D)	1.00	0.80	0.88	0.91	1 if used urea and 0 otherwise
	(0.00)	(0.40)	(0.32)	(0.28)	
Use DAP (D)	0.97	0.59	0.91	0.84	1 if used DAP and 0 otherwise
	(0.17)	(0.49)	(0.29)	(0.37)	
Use MOP (D)	0.31	0.26	0.59	0.34	1 if used MOP and 0 otherwise
	(0.46)	(0.44)	(0.49)	(0.47)	
Use right source of fertilizers (D = Dummy)	0.25	0.24	0.56	0.30	1 if used urea, DAP, and potash and 0 otherwise
	(0.44)	(0.43)	(0.50)	(0.46)	
Use fertilizer at the right time (D)	0.10	0.02	0.07	0.07	1 if used fertilizer in right time of crop requirement and 0 otherwise
	(0.31)	(0.14)	(0.26)	(0.26)	
Use fertilizer in right place (D)	0.30	0.04	0.15	0.19	1 if fertilizer applied in right place and 0 otherwise
	(0.46)	(0.20)	(0.36)	(0.39)	
Use right dose of nitrogenous fertilizer (D)	0.02	0.12	0.09	0.06	1 if fertilizer applied within plus minus standard deviation of 10% of the right dose of nitrogenous fertilizers
	(0.15)	(0.32)	(0.28)	(0.25)	
Excess use of nitrogenous fertilizers (D)	0.08	0.40	0.81	0.18	1 if nitrogen is used in excess amount (>10% of the recommended dose) and 0 otherwise
	(0.27)	(0.49)	(0.39)	(0.38)	
Socio-economic characteristics					
Female-headed households (D)	0.23	0.28	0.32	0.26	1 if a household is headed by female and 0 otherwise
	(0.42)	(0.45)	(0.47)	(0.44)	
Age of household head (in years)	48.64	48.50	47.51	48.40	Age of household head (in years)
	(12.19)	(13.36)	(12.49)	(12.63)	
Household head education (years)	4.79	5.30	5.59	5.09	Year of education of household head
	(4.68)	(4.48)	(4.67)	(4.62)	
Family size (number)	‘6.75	5.88	5.59	6.26	Household size (number)
	(3.41)	(2.65)	(2.44)	(3.06)	
Migration (D)	0.20	0.26	0.17	0.21	1 if a member of a household has migrated and 0 otherwise
	(0.40)	(0.44)	(0.38)	(0.41)	
Dalits/unprivileged (D)	0.04	0.16	0.10	0.09	1 if a household belong from Dalits/unprivileged group and 0 otherwise
	(0.20)	(0.36)	(0.30)	(0.29)	
Access to credit (D)	0.22	0.13	0.10	0.17	1 if a household has access to credit and 0 otherwise
	(0.41)	(0.34)	(0.30)	(0.38)	
Smartphone (D)	0.28	0.32	0.31	0.30	1 if a household head has a smartphone and 0 otherwise
	(0.45)	().47)	(0.46)	(0.46)	
	0.70	0.65	0.76	0.69	If annual income is from one to five lakh NRs, then 1, otherwise 0

(*Continued*)

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Table 3. (*Continued*)

Variables	Rice	Maize	Cauliflower	Overall	Variable description
Annual income from one to five lakh (D)					
	(0.46)	(0.48)	(0.43)	(0.46)	
Annual income of less than one lakh (D)	0.16	0.15	0.08	0.14	If annual income is between five to ten lakh NRs, then 1, otherwise 0
	(0.37)	(0.36)	(0.27)	(0.35)	
Cooperatives (D)	0.90	0.97	0.94	0.93	If a household has a member associated with cooperative or any other groups
	(0.30)	(0.16)	(0.24)	(0.25)	
Rural region (D)	0.69	0.88	0.78	0.77	If a household belongs to rural areas, then 1, otherwise 0
	(0.46)	(0.33)	(0.41)	(0.42)	
Agriculture characteristics					
Total farmed area (ha)	0.56	0.26	0.04	0.37	Total area cultivated (in hectare)
	(0.55)	(0.20)	(0.03)	(0.45)	
Livestock index	8.38	11.14	8.15	9.25	Livestock index
	(10.79)	(14.73)	(6.71)	(11.78)	
Hybrid variety (D)	0.26	0.65	0.64	0.46	1 if a household has grown hybrid variety and 0 otherwise
	(0.44)	(0.48)	(0.48)	(0.50)	
Irrigation facility (D)	0.29	0.15	0.25	0.24	1 if a household has access to irrigation facility and 0 otherwise
	(0.45)	(0.36)	(0.43)	(0.43)	
Contract farming (D)	0.02	0.07	0.04	0.04	1 if a household is engaged in contract farming and 0 otherwise
	(0.13)	(0.25)	(0.21)	(0.19)	
Fertilizer demonstration (D)	0.03	0.04	0.04	0.04	1 if a household has participated in fertilizer demonstration and 0 otherwise
	(0.17)	(0.20)	(0.21)	(0.19)	
Time to reach nearest cooperatives	19.98	19.54	23.96	20.52	Time taken to reach the nearest cooperative in minutes
	(16.50)	(18.69)	(16.14)	(17.25)	
Time to reach nearest agrovets	22.37	29.71	22.06	24.73	Time taken to reach the nearest agrovet in minutes
	(17.38)	(26.25)	(22.97)	(21.90)	
Ecological zone					
Terai region (D)	0.89	0.44	0.26	0.63	If a household is from Terai region, then 1, otherwise 0
	(0.32)	(0.50)	(0.44)	(0.48)	
Surveyed year is 2022 (D)	0.56	0.52	0.50	0.54	If survey was conducted in 2022, then 1, otherwise 0
Observations	461	305	160	926	

Notes: Standard deviations are in parenthesis; D indicates dummy variable (1/0).

Table 4. Pairwise correlation coefficients across 4R's fertilizer application decisions

	Coefficient	Standard errors	*p*-Value
Right time and right source	0.83	0.04	0.00
Right placement and right source	0.92	0.00	0.00
Right dose and right source	−0.09	0.08	0.22
Right placement and right time	0.75	0.04	0.00
Right dose and right time	−0.08	0.09	0.34
Right dose and right placement	−0.21	0.08	0.01

Note: Likelihood ratio test of rho21 = rho31 = rho41 = rho32 = rho42 = rho43 = 0: $chi^2(6) = 481.20$ Prob > $chi^2 = 0.0000$.

significantly more likely to apply fertilizers at the right rate. Cooperative members are more likely to apply N, P, and K fertilizers in the right place. Contract farming shows mixed effects. While farmers engaged in contract farming are more likely to adopt the right fertilizer source and placement, they are less likely to adhere to the correct nitrogen application rate.

Access to agricultural inputs and information varies with distance from cooperatives and agrovets. Farmers located closer to these resources are more likely to adopt 4R practices. Information and Communications Technology (ICT) access, particularly smartphone ownership, positively influences the adoption of the right rate of nitrogen applications. Households cultivating hybrid crop varieties are more likely to use the appropriate fertilizer types. Similarly, access to irrigation facilities enhances 4R adoption, especially regarding the right fertilizer type and placement.

Factors influencing the excessive use of nitrogenous fertilizers

Table 6 presents empirical results from the probit model assessing the determinants of excessive nitrogenous fertilizer use across rice, maize, and cauliflower farmers. To enhance interpretability, we report marginal effects rather than odds ratios, allowing for a clearer understanding of the impact of each factor on the probability of nitrogen overuse. All three crop-specific models are statistically significant.

Land size is negatively correlated with excessive nitrogen application across all three crops. The livestock index is positively associated with the probability of excessive use among rice and maize farmers. Those growing hybrid maize varieties are more likely to apply excessive nitrogen. In contrast, rice and cauliflower farmers cultivating hybrid varieties are less likely to overapply nitrogen.

Farmers with irrigation access, particularly rice and maize growers, have a higher likelihood of overusing nitrogenous fertilizers. Rice and maize farmers who have access to credit exhibit a higher probability of excessive nitrogen application.

For cauliflower farmers, proximity to agricultural cooperatives reduces the likelihood of excessive nitrogen use. Rice and maize farmers in the Terai region are less likely to overapply nitrogenous fertilizers compared to those in the hilly region. Maize farmers in rural areas have an approximately 18% lower probability of excessive nitrogen use compared to their urban counterparts.

To address concerns about the threshold's arbitrariness, we conducted a sensitivity analysis using a more conservative threshold of 20% above the recommended N dose (Supplementary Material Table S1). The results demonstrated that the signs and statistical significance of most coefficients remained consistent, reinforcing the robustness of our findings. This suggests that the observed patterns of excessive nitrogen use are stable across varying threshold definitions.

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Table 5. Factors associated with the adoption of 4Rs use of fertilizer (results from multivariate probit model)

VARIABLES	Right source	Right time	Right placement	Right rate (nitrogenous fertilizer)
1 if a household was surveyed in 2022 and 0 otherwise	−0.070	−0.028	0.246	−0.893***
	(0.149)	(0.243)	(0.191)	(0.245)
Socio-economic characteristics				
1 if a household is headed by female and 0 otherwise	0.189*	0.216	0.314**	−0.068
	(0.113)	(0.164)	(0.130)	(0.174)
Age of household head (in years)	0.019***	0.030***	0.023***	0.012*
	(0.004)	(0.005)	(0.005)	(0.007)
1 if a household belongs from Dalits/unprivileged group and 0 otherwise	0.225	0.036	−0.074	−0.545*
	(0.187)	(0.305)	(0.184)	(0.313)
Year of education of household head	0.039***	0.039**	0.047***	−0.003
	(0.012)	(0.017)	(0.013)	(0.018)
Household size (number)	−0.017	−0.010	0.005	0.012
	(0.018)	(0.024)	(0.018)	(0.026)
1 if a member of a household has migrated and 0 otherwise	0.033	−0.075	−0.018	0.159
	(0.113)	(0.165)	(0.122)	(0.171)
1 if a household borrows credit and 0 otherwise	0.147	0.153	0.045	0.313*
	(0.123)	(0.160)	(0.126)	(0.180)
1 if a household has annual income between one and five lakh rupees (NRs) and 0	−0.367***	0.235	−0.117	−0.044
	(0.116)	(0.214)	(0.128)	(0.179)
1 if a household has annual income less than one lakh rupees (NRs) and 0 otherwise	−0.501***	0.227	−0.018	0.222
	(0.174)	(0.265)	(0.196)	(0.247)
1 if a household is a member of cooperative and 0 otherwise	0.240	0.355	0.343*	−0.380
	(0.205)	(0.302)	(0.200)	(0.268)
1 if a household head has a smartphone and 0 otherwise	0.129	0.266	0.193	0.467**
	(0.134)	(0.179)	(0.148)	(0.233)
1 if household is from rural region and 0 otherwise	−0.069	−0.148	−0.442***	0.307
	(0.136)	(0.210)	(0.168)	(0.190)
Agriculture characteristics				
Total area cultivated (in hectare)	−0.326**	−0.209	0.040	−1.249**
	(0.139)	(0.188)	(0.094)	(0.489)
Livestock index	0.002	0.004	0.000	0.005
	(0.004)	(0.004)	(0.003)	(0.005)
1 if a household has grown hybrid variety and 0 otherwise	0.339***	−0.143	0.224*	0.157

(*Continued*)

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Table 5. (*Continued*)

VARIABLES	Right source	Right time	Right placement	Right rate (nitrogenous fertilizer)
	(0.097)	(0.163)	(0.117)	(0.162)
1 if a household has access to irrigation facility and 0 otherwise	0.373**	0.028	0.339**	−0.102
	(0.147)	(0.204)	(0.166)	(0.201)
1 if a household is engaged in contract farming and 0 otherwise	0.627***	0.406	0.626**	−0.839**
	(0.237)	(0.345)	(0.271)	(0.415)
Time required to visit the nearest cooperatives (in minutes)	−0.011***	−0.003	−0.008*	0.000
	(0.004)	(0.004)	(0.004)	(0.004)
Time required to visit the nearest agrovets (in minutes)	−0.002	0.003	0.003	0.004
	(0.002)	(0.003)	(0.002)	(0.004)
If the primary crop is rice, then 1, otherwise 0	−0.759***	−0.528***	0.473***	−0.251
	(0.159)	(0.204)	(0.164)	(0.270)
If the primary crop is maize, then 1, otherwise 0	−1.052***	−1.015***	−0.753***	0.345*
	(0.138)	(0.255)	(0.178)	(0.203)
Ecological zone				
1 if household is from Terai region and 0 otherwise	0.334***	0.900***	0.168	−0.013
	(0.121)	(0.214)	(0.132)	(0.174)
Constant	−0.940**	−3.743***	−2.799***	−1.773***
	(0.428)	(0.514)	(0.442)	(0.595)
Observations	926	926	926	926

Robust standard errors are in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6. Factors influencing excessive nitrogen use in Nepal: probit model marginal effects (10% above recommended rate)

Variables	Rice	Maize	Cauliflower
1 if a household was surveyed in 2022 and 0 otherwise	−0.051	−0.098	0.050
	(0.052)	(0.079)	(0.078)
Socio-economic characteristics			
1 if a household is headed by female and 0 otherwise	−0.031	−0.031	−0.016
	(0.028)	(0.060)	(0.065)
Age of household head (in years)	−0.000	0.003	0.001
	(0.001)	(0.002)	(0.003)
Year of education of household head	0.001	0.006	−0.002
	(0.003)	(0.007)	(0.006)
Household size (number)	0.002	−0.011	0.019
	(0.004)	(0.011)	(0.015)
1 if a member of a household has migrated and 0 otherwise	0.014	−0.016	–
	(0.024)	(0.055)	–
1 if a household belongs from Dalits/unprivileged group and 0 otherwise	0.016	−0.066	–
	(0.036)	(0.071)	–
	–	(0.117)	–
1 if a household borrows credit and 0 otherwise	0.055***	0.194***	−0.065
	(0.021)	(0.071)	(0.106)
1 if a household has annual income between one and five lakh rupees (NRs) and 0 otherwise	−0.031	0.021	−0.156
	(0.030)	(0.062)	(0.098)
1 if a household has annual income less than one lakh rupees (NRs) and 0 otherwise	−0.082**	0.085	−0.149
	(0.040)	(0.087)	(0.122)
1 if a household is a member of cooperative and 0 otherwise	−0.027	−0.081	–
	(0.033)	(0.147)	–
1 if a household head has a smartphone and 0 otherwise	−0.045	−0.065	0.117
	(0.028)	(0.071)	(0.083)
Time required to visit the nearest agrovets (in minutes)	0.001	0.001	−0.002*
	(0.000)	(0.001)	(0.001)
1 if household is from rural region and 0 otherwise	−0.011	−0.179**	–
	(0.044)	(0.079)	–
Agriculture characteristics			
Total area cultivated (in hectare)	−0.638***	−0.622***	−3.833***
	(0.110)	(0.173)	(0.755)
Livestock index	0.002***	0.003*	−0.000

(*Continued*)

Table 6. (*Continued*)

Variables	Rice	Maize	Cauliflower
	(0.001)	(0.002)	(0.004)
1 if a household has grown hybrid variety and 0 otherwise	−0.049**	0.226***	−0.120*
	(0.023)	(0.061)	(0.065)
1 if a household has access to irrigation facility and 0 otherwise	−0.005	0.071	0.166**
	(0.035)	(0.087)	(0.082)
1 if a household is engaged in contract farming and 0 otherwise	–	−0.441***	–
		(0.117)	
Ecological zone			
1 if household is from Terai region and 0 otherwise	−0.074***	−0.392***	−0.152**
	(0.027)	(0.057)	(0.075)
Observations	453	305	144
Wald chi-square	65.43	75.19	46.40
Pseudo-R-squared	0.54	0.25	0.26

Robust standard errors are in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Discussion

Our study highlights the suboptimal adoption of 4R nutrient management practices among smallholder farmers in Nepal. Fertilizer use varies significantly by crop and nutrient type, with 100% of rice farmers applying urea compared to 80% of maize and 88% of cauliflower farmers. Despite urea's widespread use—Nepal's most popular fertilizer—only 25% of rice and maize farmers used the right fertilizer source, and over 90% failed to apply fertilizers at the right rate.[6] Notably, only 4% of maize farmers applied fertilizers in the right place, and just 2% of all farmers applied the correct nitrogen dose. These inefficiencies suggest that improving fertilizer management by adopting the 4Rs could substantially reduce yield gaps corroborated with earlier studies in similar agroecological zones in Nepal (Pandit *et al.,* 2025).

The observation that farmers apply fertilizers at the right place but do not consistently apply the right rate, at the right time, or use the right source offers several critical insights into the fertilizer management practices and highlights areas for targeted intervention. The correct placement of fertilizer is often easier to observe and adopt because farmers can directly see the effect of placement on crop growth (e.g., root zone application leading to better plant vigour). However, right rate, time, and source require a deeper understanding of nutrient dynamics, soil fertility, and crop nutrient requirements, which may not be as intuitive. When farmers understand best practices, resource constraints may force them to make suboptimal decisions.

Nepal's reliance on fertilizer imports exacerbates the issue. The government spent 9,071 million NPR on fertilizer subsidies in 2020, with 74% allocated to urea, 25% to DAP, and 1% to MOP (Thapa *et al*., 2025). Yet, chronic fertilizer shortage persist—only 60% of national demand is met (Gautam *et al.,* 2022; World Bank, 2016). Famers often cannot access recommended fertilizer doses during the critical growing season. A study found that just 25% of farmers could purchase their full fertilizer needs (Kyle, Resnick and Karkee 2017), and many are willing to pay significantly above market prices to secure supplies (Thapa *et al*., 2025). These systemic issues hinder the adoption of 4R practices, leading to inefficient fertilizer use despite the high economic cost.

Our MVP model revealed significant socio-economic and agricultural factors influencing 4R adoption. Older, more experienced farmers show a higher likelihood of adopting 4R practices, possibly due to their accumulated knowledge and understanding of the long-term benefits of balanced fertilizer use. Dalit households are less likely to apply the right fertilizer dose, reflecting systemic inequalities. Dalits, often smallholder farmers with lower incomes and education levels, face structural barriers to technology adoption (Kumar *et al.,* 2020). Our data show household heads from Dalits have lower education levels (4.3 years) compared with Brahmin/Chhetry (6.1) and Janajati (4.7) household heads (Table S2). Further, Dalits also have higher poverty rates compared to Brahmin/Chhetri and Janajati households, limiting their access to resources and information.

Education significantly increased the adoption rate of 4R practices, suggesting that more educated farmers have a better understanding of the benefits of efficient fertilizer use. Our findings align with previous studies that identify education as a strong predictor of agricultural technology and fertilizer adoption (Omamo *et al.,* 2002; Takeshima *et al.,* 2016). Smallholders are more inclined to adopt 4R practices, likely due to the need to maximize productivity on limited land. However, small landholders are also more prone to overapply nitrogen, aiming to boost yields.

Credit access facilitates fertilizer purchases, increasing the likelihood of correct application rates. Cooperative membership also plays a crucial role, improving access to fertilizers and information. Farmers closer to cooperatives are more likely to adopt 4R practices, underscoring the importance of local institutions in promoting sustainable agriculture. Smartphone ownership enhances 4R adoption, particularly for the correct nitrogen rate. ICT tools provide timely

[6]Crops can obtain the required nitrogen from DAP, other nitrogen-based chemical fertilizers, and organic manure. This study does not imply that urea is always the appropriate or sole source of nitrogen.

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information and guidance, as demonstrated in other contexts where mobile-based interventions improved agricultural practices and yields (Casaburi *et al.*, 2014; Giulivi *et al.*, 2023).

Farmers growing hybrid varieties or with irrigation access are more likely to adopt specific 4R practices, especially regarding fertilizer type and placement. Hybrid crops often require more inputs, while irrigation increases nutrient availability, encouraging higher fertilizer use. However, this can also lead to overapplication, particularly of nitrogen, as farmers aim to maximize yield potential.

The probit model revealed that several socio-economic and agricultural factors contribute to the excessive use of nitrogenous fertilizers. Smallholders tend to overapply nitrogen, aiming to boost yields on limited land. Livestock ownership and credit access increase the likelihood of nitrogen overuse in rice and maize, potentially due to higher input affordability. Regional disparities influence fertilizer practices: farmers in the Terai region apply less excessive nitrogen than those in the hills, while rural maize farmers are 18% less likely to overuse nitrogen compared to urban farmers. Proximity to cooperatives reduces nitrogen overuse, particularly among cauliflower farmers, by improving access to information on proper fertilizer use.

Hybrid crops often have higher nutrient requirements due to their enhanced yield potential, and this has important implications for defining the 'right dose' in our analysis. Considering this, applying a uniform recommended dose across both hybrid and landrace varieties could indeed lead to a misclassification of what constitutes excessive fertilizer use. Extension services should consider promoting variety-specific fertilizer guidelines that account for the higher demands of hybrid crops, helping farmers optimize input use while avoiding true overapplication.

Conclusion and policy implications

This study examined the adoption of 4R soil nutrient management practices among smallholder farmers in Nepal, focusing on rice, maize, and cauliflower cultivation. Using data from two survey rounds (2021 and 2022), the findings reveal that the overall adoption of 4R practices remains low, particularly regarding the right rate and timing of nitrogen application. While cauliflower farmers demonstrated relatively higher adherence to 4R practices, the majority of rice and maize farmers continue to apply fertilizers inefficiently, resulting in potential yield gaps and reduced fertilizer efficiency.

Our analysis highlights that socio-economic and demographic factors significantly influence 4R adoption. Female-headed households and older farmers are more likely to adopt specific 4R practices, suggesting that experience and gender dynamics play a role in nutrient management decisions. Marginalized groups, such as Dalits, face systemic barriers to adopting optimal fertilizer practices, reflecting broader social and economic disparities. Education is a key driver of 4R adoption, though its impact varies across specific practices. More educated farmers are better positioned to understand and implement sustainable nutrient management strategies. Farmers with credit access are more capable of purchasing the appropriate quantity and variety of fertilizers, increasing the likelihood of applying fertilizers at the right rate. Smartphone ownership enhances nitrogen management, enabling farmers to access real-time agricultural information and best practices. Proximity to cooperatives and engagement in contract farming positively influence the adoption of 4R practices by improving input accessibility and promoting knowledge-sharing. Farmers cultivating hybrid crops or with access to irrigation are more likely to adopt proper fertilizer types and application methods. However, these farmers also face a higher risk of excessive nitrogen use, underscoring the need for targeted extension services and fertilizer-use guidelines.

To promote efficient and balanced fertilizer use in Nepal, several policy interventions are recommended. Farmer education and extension services need to be strengthened. Training programmes and field demonstrations could be implemented to raise awareness about 4R nutrient

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management and its long-term benefits. Government could improve fertilizer accessibility and affordability. The current subsidy structure could be reformed by increasing support for DAP and MOP to encourage balanced nutrient use beyond urea. Government could provide affordable credit options to enable smallholders to invest in the recommended quantity and variety of fertilizers. The ICT tools need to be leveraged such as smartphone applications and SMS-based advisory services—to disseminate information on best practices. Cooperatives need to be strengthened as key actors in fertilizer distribution and knowledge-sharing, ensuring that smallholders have access to inputs and training. Government could implement inclusive policies that provide tailored support for disadvantaged groups, such as Dalit farmers, to bridge adoption gaps and promote equity.

Nepal's fertilizer challenges—marked by heavy reliance on imports, inefficient use, and widespread subsidies—mirror those faced by many developing countries, particularly in South Asia. The insights from this study can inform fertilizer management strategies in similar agricultural settings, supporting global efforts towards sustainable agriculture. By promoting 4R nutrient management, Nepal can reduce fertilizer dependency, minimize environmental harm, and enhance agricultural productivity. Ultimately, these efforts align with the broader objectives of the United Nations Sustainable Development Goals (SDGs), particularly those related to food security, climate action, and responsible resource use. Future research could explore the impact of fertilizer supply chain dynamics and government distribution mechanisms on farmers' fertilizer use patterns, as this remains a critical issue for ensuring sustainable nutrient management.

The study possesses some limitations. The study primarily relies on self-reported survey data, which can introduce recall bias, especially in estimating fertilizer application rates and timings. The absence of plot-level data and detailed information on soil fertility limits the ability to tailor nutrient recommendations or fully capture site-specific management practices. The study focuses on chemical fertilizer use but excludes the quantification of organic inputs (e.g., farmyard manure, green manures). This omission may lead to an underestimation of total nutrient inputs, particularly for farmers who integrate organic fertilizers into their management strategies. The 10% deviation from recommended nitrogen rates used to define excessive application, though practical, is somewhat arbitrary and may not accurately reflect the ecological or agronomic thresholds for overuse across different soil types and crop conditions. With data collected over just two survey rounds, the study captures a snapshot rather than long-term trends. Seasonal variability or yearly fluctuations in fertilizer availability and prices could influence farmers' practices, limiting the generalizability of the findings. The findings are specific to Nepalese smallholder farmers and may not be directly applicable to regions with different agroecological conditions, market dynamics, or policy frameworks. Broader implications should be drawn with caution.

Our sampling strategy could still introduce minor biases: farmers who are more connected to local cooperatives or agricultural extension services may have been more likely to be included in the sampling frame, potentially leading to slightly higher adoption rates of certain best practices. The use of community registries may have unintentionally excluded informal farmers or those in more remote locations, who may exhibit different fertilizer use behaviours. Future studies could adopt larger, more randomized sampling frameworks or use longitudinal data to further minimize selection bias. Farmers selected in the survey cultivate multiple crops. We acknowledge the non-independence of observations from the same farmers growing rice, maize, and cauliflower. Our survey design was not able to focus exclusively on farmers growing an individual crop.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479725100203

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