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Nitrogen Management Utilizing 4R Nutrient Stewardship: A Sustainable Strategy for Enhancing NUE, Reducing Maize Yield Gap and Increasing Farm Profitability

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Abstract: The imbalanced use of fertilizers, particularly the inefficient application of nitrogen (N), has led to reduced nitrogen use efficiency (NUE), lowered crop yields and increased N losses in Nepal. This study aimed to enhance yields, NUE and farm profitability by optimizing N fertilizer rates, application timing and methods through multilocation trials and demonstrations. In 2017, 57 field trials were conducted in two mid-hill districts using a completely randomized block design. The treatments included control (CK), NPK omission (N0, P0 and K0), variable N rates (60, 120, 180 and 210 kg N ha^{-1}) and top-dressing timings (120 kg N ha^{-1} applied at knee height and shoulder height, V6, V10 and V8 stages). A full dose of recommended P (60 kg ha^{-1}) and K (40 kg ha^{-1}) were applied at planting, while N was top-dressed in two equal splits at knee-height and shoulder-height growth stages for P and K omission treatments, as well as for treatment with variable N rates. Grain yields responded quadratically, with optimum N rates ranging from 120 to 180 kg ha^{-1} across the districts. N applied at 120 kg ha^{-1} and top-dressed at V6 and V10 increased maize yield by 20–25%, partial factor productivity of nitrogen (PFPN) by 12%, agronomic efficiency of nitrogen (AEN) by 21% and gross margin by 10% compared to conventional knee and shoulder height application. In 2018 and 2019, fertilizer BMPs, including V6 and V10 top-dressing and the urea briquette deep placement (UDP) were demonstrated on 102 farmers' fields across five mid-hill districts to compare their agronomic and economic significance over traditional farmers' practice (FP). UDP, validated in 2018 field trials, increased yields by 34% (8.8 t ha^{-1}) and urea top-dressing at V6 and V10 increased yield by 33% (8.7 t ha^{-1}) compared to FP (5.8 t ha^{-1}), reducing the average yield gap by 3.0 t ha^{-1}. Moreover, the gross margin was increased by 39% (V6 and V10) and 40% (UDP) over FP. The findings highlight the need for widespread adoption of fertilizer BMPs to close the yield gap and maximize profitability with minimal nitrogen footprint.

Keywords: nitrogen management; BMPs; maize productivity; NUE; farm income; Nepal

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1. Introduction

Maize (*Zea mays* L.) ranks as the third most important food and feed crop worldwide, following rice and wheat, and is the second most important food security crop in Nepal after rice. Maize is grown across diverse agro-ecological zones in terai (tropical) and mid-hill (sub-tropical and temperate) regions for feed, food and forage. Maize occupies 43% of cereal crop area and contributes 53% of cereal production [1]. In terai, most commercial farmers grow maize under irrigated conditions, while in the mid-hills it is generally cultivated under rainfed and nutrient-limited conditions [1,2]. Nepal's national maize productivity is 3.1 t ha^{-1}, which is considerably lower than that of other south Asian countries [3]. This yield gap (difference between attainable maize yield and actual yield in farmers' yield) is mainly due to declining soil fertility, limited innovation and low adoption of best management practices (BMPs), including improper use of N fertilizers.

In Nepal, low soil fertility and nutrient depletion are due to factors like erosion, resource depletion, intensified cropping with repeated cultivation of nutrient mining crops, limited legume use in crop rotation, limited organic inputs such as compost and biochar, and imbalanced fertilizer applications [4–6]. Farmers often deviate from the recommended NPK fertilizer dose (120:60:40 kg NPK/ha), especially nitrogen, leading to significant variations in application rate. Most farmers apply urea, while moderate numbers apply di-ammonium phosphate (DAP), and very few use muriate of potash (MOP) or secondary or micronutrients. The higher application of urea relative to DAP and MOP is mainly attributed to the greater price subsidy for urea (65–70%), compared to DAP (25–30%) and MOP (30–32%) [7], along with lack of information on fertilizer BMPs available to farmers. This imbalance in fertilizer application has led to decreased fertilizer use efficiency, increased losses, reduced maize yields and significant yield gaps. Therefore, the use of balanced fertilizers is crucial for replenishing soil nutrients, maintaining soil health and fertility and ultimately narrowing yield gaps [8].

Nitrogen provides essential plant nutrients and is often the most limiting factor for crop growth and development globally, including in Nepal [9]. A deficiency of N results in reduced chlorophyll production, influencing the photosynthetic activities, causes stunted growth, yellowing of leaves and ultimately results in lower yields with poor grain quality [10,11]. A sufficient amount of nitrogen should be available during crop growth and development stages to achieve higher dry matter production, photosynthetic efficiency, crop yields and profits [10,12]. While optimal N fertilization boosts yields, over-application lowers nitrogen use efficiency (NUE) and leads to environmental losses through leaching, surface run-off, volatilization, and emission of nitric and nitrous oxides (potent greenhouse gases) [10]. The nitrogen rate varies based on diverse agroecological zones, climate, soil types, crop types and irrigated vs. unirrigated conditions, highlighting the needs for site-specific N management over blanket recommendations [13,14].

A key strategy for efficient fertilizer management is the use of the 4Rs nutrient stewardship (right source, right rate, right time and right place), particularly for nitrogen fertilizers to improve N recovery, minimize losses and enhance crop productivity [15,16]. Urea, widely used among farmers, is often applied without considering the 4Rs principle. Application rates and the timing of fertilizers vary widely among farmers, resulting in regional differences in soil fertility, crop yields, income levels and environmental impacts. The optimum rate and timing of N fertilization are considered as the most critical factors for enhancing crop productivity, as they align nutrient availability with plant demands [17,18]. Maize has its maximum N demand during the rapid vegetative growth phase, with N uptake depending on soil available nitrogen [11,19]. Since granular urea is highly water-soluble and can easily be lost from the soil through different pathways, identifying the right timing for application is one of the most effective strategies for N management [20]. Moreover, farmers normally apply urea by spreading on the soil surface as a basal application during planting, resulting in a lower NUE of only around 20–30%, with over 60% of N being lost to the environment mainly through volatilization [21,22]. It is crucial to incorporate the urea into soil or apply directly to the root zone to reduce such losses and enhance N uptake by plants. Recently, deep placement of urea briquette (UB) or root zone application has demonstrated higher NUE, crop yields and income [23,24]. To produce UB, conventional granular urea is compressed into 1–3 g pellets in a machine and applied to root zone 7–10 cm below the soil surface. A single application of UB with deep placement (UDP) has shown improved N recovery efficiency, allowing a reduction in N application rates, as the slow release mechanism of UB ensures a consistent supply of N throughout the crop-growing season [23,25].

It is crucial to identify fertilizer best management practices (BMPs) utilizing the 4Rs principle, especially nitrogenous fertilizers, to increase maize yields, farm profitability and NUE and to reduce the agricultural nitrogen footprint [26–28]. Research and development for the 4Rs of fertilizer management through multilocation on-farm trials and demonstrations are still limited in Nepal. Most research on nitrogen rate and timing is conducted in research stations, and the results often differ significantly from on-farm trials carried out under diverse agro-ecological conditions and management practices [29]. Moreover, on-farm studies on the application of urea briquettes using deep placement techniques remain limited. Thus, it is essential to investigate the N response in farmers' fields and recommend fertilizer best management practices (BMPs) at the local farm level to achieve precise and effective outcomes. The present study aimed to optimize nitrogen rate, timing and placement (UDP) following the 4Rs principle to enhance maize yields and NUE and demonstrate these practices as "fertilizer BMPs" in farmers' fields. The underlying hypothesis is that fertilizer BMPs, which integrate balanced NPK fertilization and the 4Rs principle for N management, will improve NUE, increase grain yields, and enhance farm profitability compared to traditional farming practices (FPs).

2. Materials and Methods

2.1. Site Description

Multilocation field trials and demonstrations were conducted across five districts (Dang, Surkhet, Doti, Palpa and Kavre) in mid-hills with elevations ranging from 600 to 2500 m above sea level over three years from 2017 to 2019 (Figure S1). In 2017, multilocation fertilizer trials were conducted in the mid-hills of Dang and Surkhet districts. In 2017, the average minimum and maximum temperatures during the maize growing season (April to September) were 20.0 °C (ranging from 115.8 °C to 23.7 °C) and 30.8 °C (ranging from 28.5 °C to 34.2 °C), respectively (Figure 1), with a cumulative rainfall of 1460 mm. In 2018 and 2019, demonstrations in farmers' fields were conducted across five mid-hill districts (Dang, Surkhet, Doti, Palpa and Kavre). In 2018, the average temperature ranged from a minimum of 18.3 °C (15.7–22.1 °C) to a maximum of 29.2 °C (25.1–33.9 °C), with a cumulative rainfall of 1477 mm. Similarly, in 2019, average temperature ranged from a minimum of 20.0 °C (16.5–23.9 °C) to a maximum of 30.5 °C (26.1–34.2 °C), with total rainfall of 1294 mm.

2.2. Soil Characteristics

From each plot, soil samples were collected before maize plantation (April) from five locations in a "W" pattern with a soil auger at a depth of 10 cm, then pooled into a composite sample for each plot. Each composite sample was analyzed for soil pH, organic matter (OM), texture, total N and available P_2O_5 and K_2O using wet chemistry methods. Soil samples were dried at 40 °C for three days, passed through a 2 mm sieve and ground before analysis. Soil texture was analyzed through the hydrometer method [30]. Soil pH was measured in a 1:2.5 water suspension using a digital pH meter (buffering at pH 7 and 4). Organic carbon was determined as per the Walkley and Black method [31]. Total N was analyzed through Kjeldahl's method. Available P was determined through modified Olsen's bicarbonate [32] and available K through the neutral ammonium acetate method using a flame photometer. Details about the soil analytical process are shown in the

Supplementary Materials (Description S1). The soil was characterized as loamy, Inceptisol (USDA classification system), across the maize trial and demonstration sites (Table 1). Soil pH ranged from 5.8 to 6.4, OM from 1.6 to 3.2%, total N from 0.10 to 0.15%, available P from 40.0 to 90.0 mg kg^{-1} and available K from 110.6 to 236.0 mg kg^{-1}.

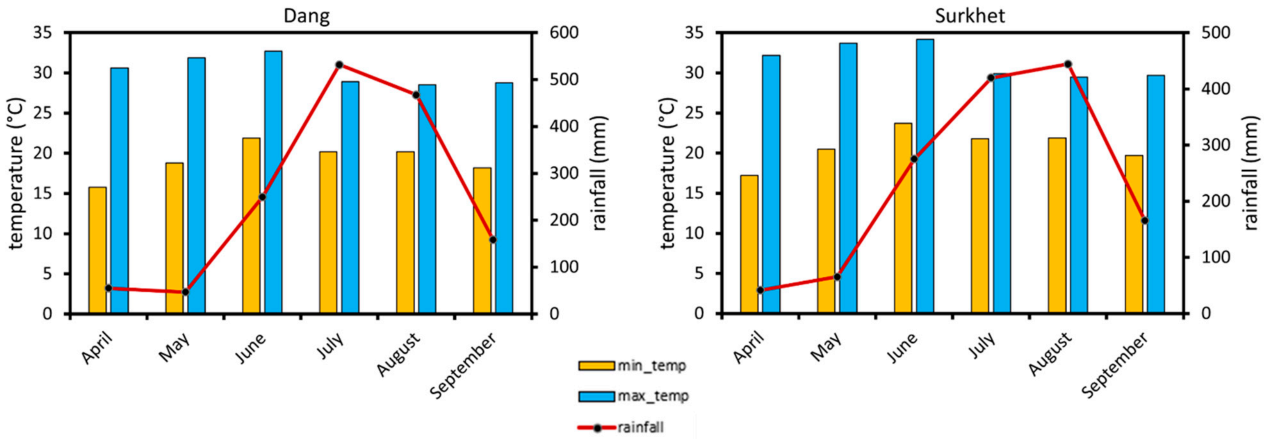

Figure 1. Annual minimum and maximum temperature along with rainfall in field trial sites across Dang and Surkhet, 2017. Temperature and rainfall data were extracted from the National Oceanic and Atmospheric Administration (NOAA) and rainfall estimates from Rain Gauze and Satellite Observations (CHIRPS).

Table 1. Soil characterization across the study districts.

Parameters	**Districts**				
	Dang	**Surkhet**	**Doti**	**Palpa**	**Kavre**
Texture	Loam	Loam	Loam	Loam	Loam
Sand (%)	40 ± 2	38 ± 2	43 ± 1	45 ± 2	44 ± 1
Silt (%)	39 ± 1	47 ± 1	42 ± 2	40 ± 1	38 ± 1
Clay (%)	21 ± 1	15 ± 1	15 ± 1	15 ± 1	18 ± 1
pH	6.43 ± 0.22	6.35 ± 0.24	6.21 ± 0.25	6.50 ± 0.10	5.78 ± 0.03
OM (%)	2.48 ± 0.58	2.43 ± 0.50	3.12 ± 0.23	3.25 ± 0.20	1.59 ± 0.04
Total N (%)	0.12 ± 0.02	0.13 ± 0.02	0.19 ± 0.01	0.15 ± 0.01	0.10 ± 0.01
Available P (mg kg^{-1})	51.3 ± 27.9	44.2 ± 20.3	90.0 ± 17.2	40.0 ± 8.0	65.5 ± 12.0
Available K (mg kg^{-1})	110.6 ± 46.8	133.6 ± 53.2	140.2 ± 16.3	236.0 ± 32.2	200.5 ± 25.0

2.3. Experimental Design and Field Demonstration Set-Up

In 2017, a total of 57 multilocation fertilizer trials were conducted on farmers' fields across 19 municipalities in Dang (Shantinagar, Purandhara, Panchkaule, Dhikpur, Laxmipur, Dhuruwa, Pawannagar, Shreegau and Hapur) and Surkhet (Neta, Babiyachaur, Ramghat, Gadhi, Guthu, Ghumkhare, Lekhparsa, Kalyan, Maintada-03 and Maintada-04) districts. In each district, cooperatives dealing with fertilizer distribution were selected purposively, and trials were conducted by selecting three farmers (n = 3) per cooperative. Ten treatments, including control (CK), NPK omission (N0, P0 and K0), variable N rates (60, 120, 180 and 210 kg N ha^{-1}) using conventional urea (N-60, N-120, N-180 and N-210) and N application timing treatments (N top-dressing at knee height (25–30 days after sowing, DAS) and shoulder height (50–55 DAS) stages (K & S), V6 & V10, and V8 stages) were arranged in a randomized complete block design (RCBD) (Table 2). The treatments in each farmer's field were randomized through simple random sampling using a lottery method. The size of each treatment plot was 25 m^2 (5 m × 5 m), totaling 250 m^2 per farmer's field. The control plot received no fertilizers. Phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied at recommended rates (60:40 kg P_2O_5: K_2O ha^{-1}) in the form of di-ammonium phosphate (DAP) and muriate of potash (MOP). In the P omission plot, single super phosphate (SSP) was used to ensure zero N. Nitrogen content from DAP (18%) was deducted when calculating the required amount of nitrogen from urea.

Table 2. Description of treatments in fertilizer trials and demonstrations.

	Field Trials										
	Treatment Code	**Treatment Description**	**Fertilizer Application Rates**						**Urea/UB Application Timing**	
			N	**P**	**K**	**Urea/UB Kg ha^{-1}**	**DAP**	**MOP**	**1st Top-Dress**	**2nd Top-Dress**
1	CK	Control	0	0	0	0	0	0	-	-
2	N0	N omission	0	60	40	0	130	67	-	-
3	P0	P omission	120	0	40	261	0	67	Knee height	Shoulder height
4	K0	K omission	120	60	0	210	130	0	Knee height	Shoulder height
5	N-60	N applied at 60 kg ha^{-1}	60	60	40	79	130	67	Knee height	Shoulder height
6	N-120	N applied at 120 kg ha^{-1}	120	60	40	210	130	67	Knee height	Shoulder height
7	N-180	N applied at 180 kg ha^{-1}	180	60	40	340	130	67	Knee height	Shoulder height
8	N-210	N applied at 210 kg ha^{-1}	210	60	40	405	130	67	Knee height	Shoulder height
9	V8	N top-dressed at 8-leaf stage	120	60	40	210	130	67	V8 stage	-
10	V6 & V10	N top-dressed at six-leaf stage (V6) and ten-leaf stage (V10)	120	60	40	210	130	67	V6 stage	V10 stage
	Field demonstrations—BMPs									
1	V6 & V10 (BMP)	120:60:40 kg NPK/ha, urea top-dressed at V6 and V10 growth stage	120	60	40	210	130	67	V6	V10
2	UDP (BMP)	90:60:40 kg NPK/ha, one time application of urea briquette (UB) with deep placement (UDP)	90	60	40	145	130	67	Basal application during planting	-
3	FP	Traditional practices by farmers								

During land preparation, each plot was plowed two to three times with a moldboard plow. A full dosage of DAP and MOP was applied 5–7 cm apart from the seed sowing line and 5 cm below the soil surface during planting as a basal application. Hybrid maize with a seed rate of 25 kg ha^{-1} was sown at a depth of 5 cm with a spacing of 75 cm × 25 cm following line sowing methods. In P omission (P0), K omission (K0) and variable N rate treatments (N-60, N-120, N-180 and N-210), urea was top-dressed in two equal splits at knee-height and shoulder-height stages. A detailed description of treatments with fertilizer rates and urea top-dressing timing is provided in Table 2. Maize was grown under rainfed conditions. Weeding was carried out twice (30 and 60 days after sowing). Other agronomical practices such as control of pests and diseases were uniform for all treatments and performed as and when required.

In 2018 and 2019, fertilizer treatments that achieved higher NUE and maize yields in 2017 were identified as "fertilizer BMPs" and demonstrated on 102 farmers' fields. Cooperative farmers with large farm areas and accessible locations were selected for these demonstrations, enabling more community participation during farmer field schools to scale out the technologies. One such BMP included applying fertilizer at 120:60:40 kg NPK ha^{-1} with N top-dressed in two equal splits at the V6 and V10 growth stages. This practice was demonstrated across five mid-hill districts, including three additional districts (Doti, Palpa and Kavre) with similar agroecological conditions. Additionally, the project identified urea briquette (UB) with deep placement technology (UDP) as another effective BMP for nitrogen fertilizer management. Multilocation on farm trials conducted across the five mid-hill districts (Dang, Surkhet, Doti, Palpa and Kavre) in 2018 showed that UB applied at a 25% lower N rate (90 kg N ha^{-1}) increased PFPN by 73% and AEN by 43% while also producing higher maize yields and farm profit compared to the conventional urea applied at the recommended rate (120 kg N ha^{-1}). Both treatments received the same rates of P (60 kg ha^{-1}) and K (40 kg ha^{-1}). Consequently, UDP was demonstrated in farmers' fields across these districts in 2019. The demonstrations included both BMPs (N top-dressing at V6 & V10 and UDP) along with a reference farmer practice plot (FP), with each plot covering 150 m^2 to showcase the potential of BMPs to increase yields and income and to reduce yield gaps. Details on the rate of NPK fertilizer application and the timing of nitrogen application with urea and urea briquettes during these field demonstrations are presented in Table 2.

2.4. Grain Yields, PFPN and AEN

Maize crop was harvested upon maturity to record biomass and grain yields from the field trials and demonstrations. A 50 cm border row was excluded from all plots. During crop cuts in field trials, three 1 m^2 quadrants (totaling 3 m^2) were selected randomly and harvested manually. Similarly, in demonstration plots with two BMPs and one farmer's practice (FP), maize crop cut was conducted from three quadrants each with 3 m^2 (totaling 9 m^2). Grain moisture content was measured with a moisture meter, adjusted to 14% moisture corrected grain yields. Data on NPK fertilizer rates applied in the farmers' practice fields were collected through the farmers' survey. A total of 102 farmers were interviewed using structured questionnaires through the open data kit (ODK).

Nitrogen use efficiency (NUE) was calculated as the partial factor productivity of nitrogen (PFPN) [PFPN = YN/FN] and agronomic efficiency of nitrogen (AEN) [AEN = (YN-Y0)/FN], where YN is grain yield with applied nitrogen (kg ha), Y0 is the grain yield without nitrogen fertilizer and FN is the amount of nitrogen applied [9]. PFPN and AEN were calculated for all N-receiving treatments, including variable N rates (N-60, N-120, N-180 and N-210) and three N timing treatments (knee and shoulder height, V6 & V10, and V8 stages).

2.5. Economic Analysis

An economic assessment was conducted using the yield response data from the field trials (control and N omission) and field demonstrations, including two BMPs (urea top-dressed at V6 & V10 growth stages and UDP) along with the farmer's practice (FP). The objective of economic analysis was to compare the profitability of fertilizer BMPs over farmers' existing crop management practices. Total variable cost (TVC) accounted for the cost of seed, fertilizers and labor for fertilizer applications and other agronomical practices such as weeding, pest management and harvesting. TVC and farm gate prices were based on local market rates and are provided in the Supplementary Materials (Table S1). The maize selling price was USD 219 per ton, and the gross margin (GM) was calculated as the differences between crop salet income and TVC [25].

2.6. Data Analysis

The data were analyzed using R software, version 3.6.2 [33]. A mixed-effects model was used for trial data, using the 'lme4' package and fitted by the Restricted Maximum Likelihood (REML) model to assess the effect of treatments (fixed effect) on maize yield across district locations, with municipalities included as random factors. A post hoc Tukey test was used to identify the least significant differences (LSD) between treatment means for maize yields, PFPN and AEN. To identify the optimum N rates for yields, both linear and quadratic regressions were performed, and the best fitted model was selected to explain the relationship between N rates and yields. K-means clustering was applied to partition yield levels into k clusters for each treatment, allowing evaluation of the relationship between soil characteristics and maize yields across the trial locations. Moreover, a linear regression model was used to assess the relationship between soil chemical properties (pH, OM, total N and available P and K) and yields from the control plot across districts. For the field demonstration data, a t-test was performed on 2018 results to compare fertilizer BMPs (N top-dressed at V6 & V10) and farmers' practice (FP). In 2019, a one-way ANOVA was used to assess the effect of two fertilizer BMPs (N top-dressed at V6 & V10 and UDP) and FP, followed by a post hoc Tukey test to identify the differences in maize yields. The difference between treatments was significant at $p < 0.05$, unless stated otherwise.

3. Results

3.1. Grain Yields

Both fertilizer treatments (Figure 2a–c) and location across the district (Figure 2d) showed significant variation in maize yield, while no interaction was observed between treatment and location.

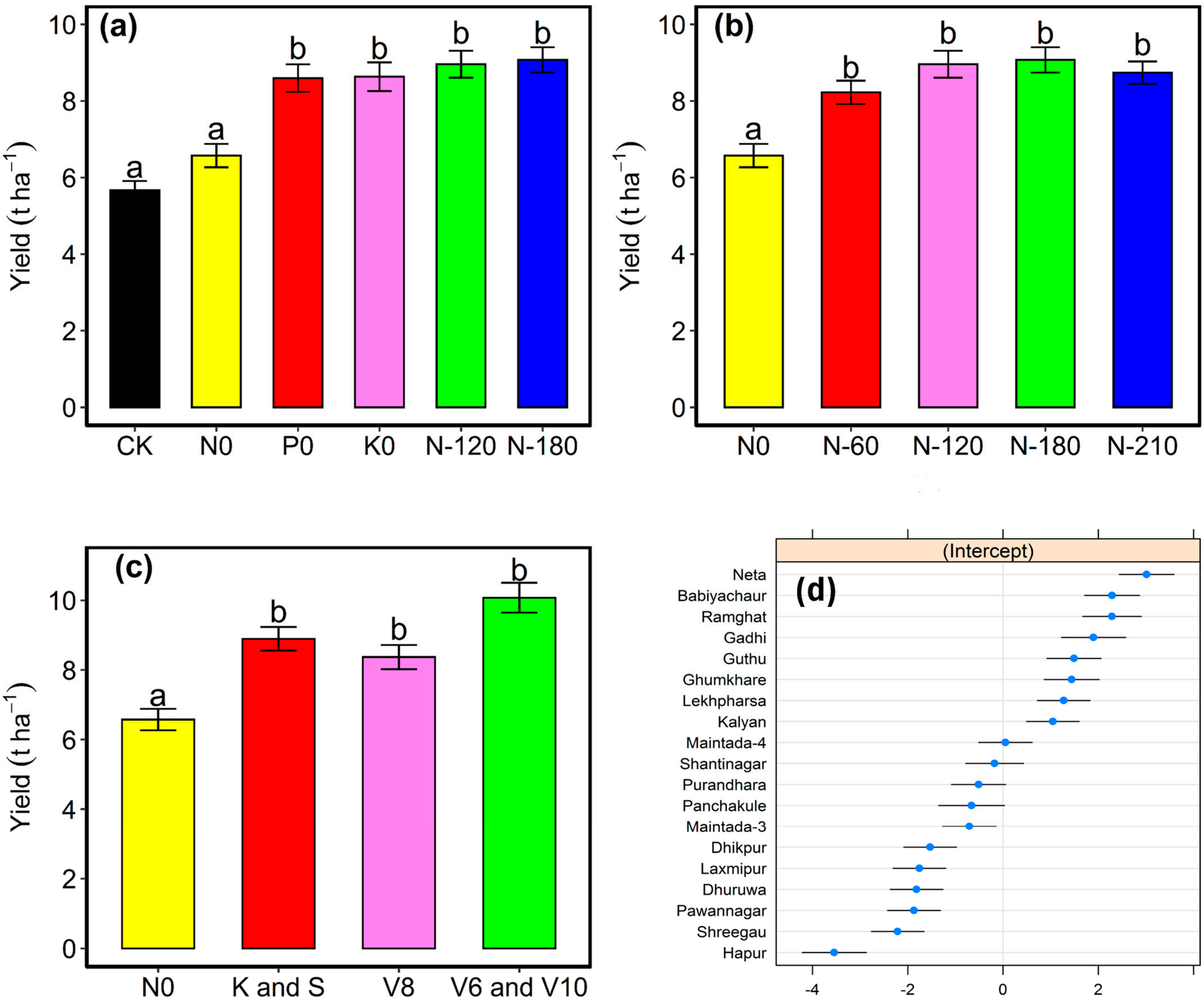

Figure 2. Response of NPK omission (**a**), varied N rate (**b**) and N timing (**c**) on average maize yield (mean ± SE). Location effect on maize yield across trial sites in Dang and Surkhet following the mixed-effects model (**d**). Different letters above a bar denote significant differences between the treatments (post hoc Tukey test, $p < 0.05$).

The NPK omission plot indicated that N is the most limiting nutrient for maize compared to P and K (Figure 2a). On average, N0 reduced yield by 2.4 t ha^{-1} (27%) as compared with the recommended rate (N-120). Negligible yield reductions of 0.3 t ha^{-1}

(3.5%) were observed with both P0 and K0 relative to the recommended rate. There was no difference in yield between the control (CK) and N0, while significant differences were observed between the CK and both P0 and K0, illustrating N as the key limiting nutrient for maize growth and development.

Different N rates showed significant effect on maize yield across the district locations (Figure 2b). N-60, N-120, N-180 and N-210 increased yield by 20% (8.2 t ha^{-1}), 27% (8.9 t ha^{-1}), 28% (9.0 t ha^{-1}) and 25% (8.7 t ha^{-1}), respectively, compared to N0 (6.5 t ha^{-1}). Maize yield responded quadratically to the added N fertilizer rates in both Dang (R^2 = 0.98) and Surkhet (R^2 = 0.99) districts (Figure 3). Based on the N response curve, the optimum rate for maize could be between 120 and 180 kg N ha^{-1} across the districts. Further addition of N fertilizer beyond 180 kg ha^{-1} reduced maize yields.

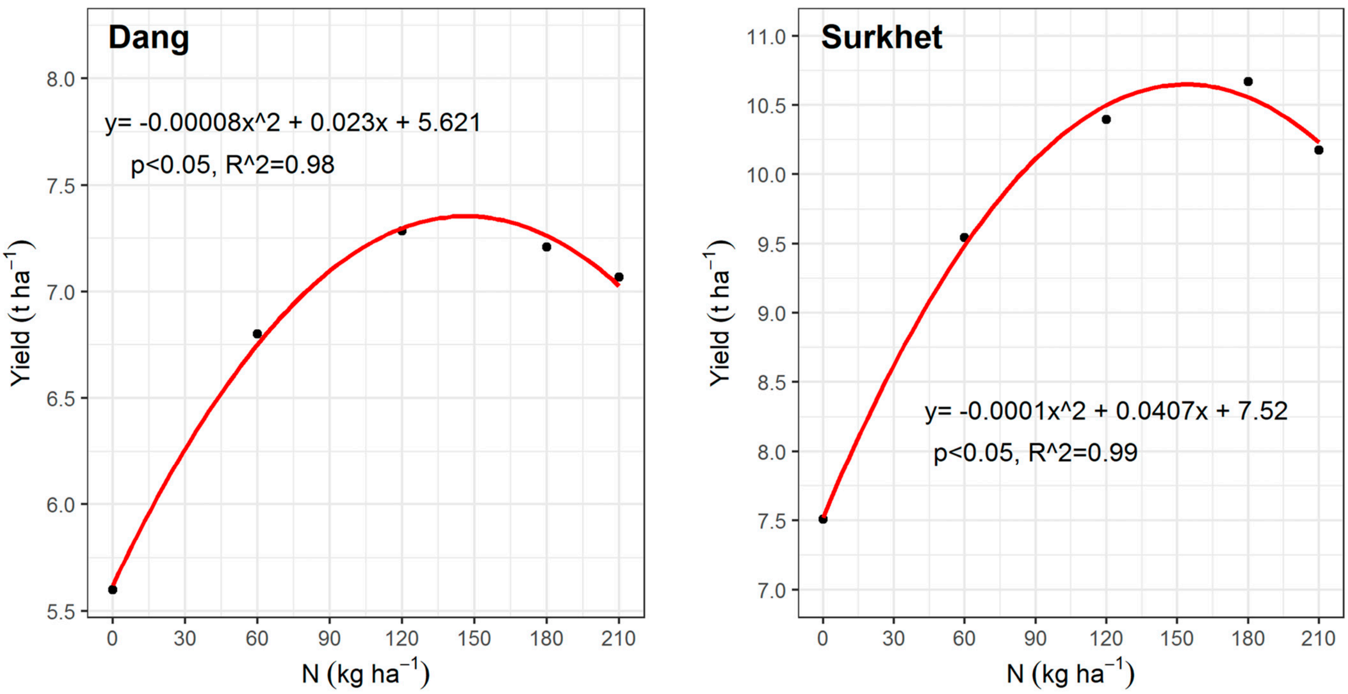

Figure 3. Response of nitrogen fertilizer addition at five different rates on average maize yield in Dang and Surkhet districts.

Nitrogen applied at the recommended rate (120 kg N ha^{-1}) and top-dressed at three different timings showed significant variation in maize yield (Figure 2c). Urea top-dressed at the knee-height and shoulder-height (K & S), V8, and V6 & V10 maize growth stages increased yield by 27% (8.9 t ha^{-1}), 21% (8.3 t ha^{-1}) and 36% (10.1 t ha^{-1}), respectively, compared to the N0 treatment.

3.2. Clustering Soil Properties and Maize Yields

Three yield clusters were identified (k = 3), with mean yields of 5.5 (n = 195), 11.8 (n = 162) and 8.4 t ha^{-1} (n = 262), and yields were further clustered by treatment to assess the relationship between soil characteristics and maize yield (Figure S2). In the control (CK) treatment, three yield clusters were formed, with cluster means of 7.1 (n = 19), 5.4 (n = 10) and 3.3 t ha^{-1} (n = 10), respectively. For each cluster, soil chemical properties (pH, OM, total N and available P and K) and yields were plotted, and no association between soil properties and yield clusters was observed (Figure S2). A similar trend was observed for other treatments, where soil chemical properties did not influence yield variation.

3.3. Nitrogen Use Effeciency (NUE)

Different nitrogen rates (N-60, N-120, N-180 and N-210) and nitrogen application timing (K & S, V6 & V10, and V8) showed significant differences in PFPN and AEN across the districts (Figure 4). PFPN and AEN as disaggregated by the districts are provided in the Supplementary Materials (Figure S3).

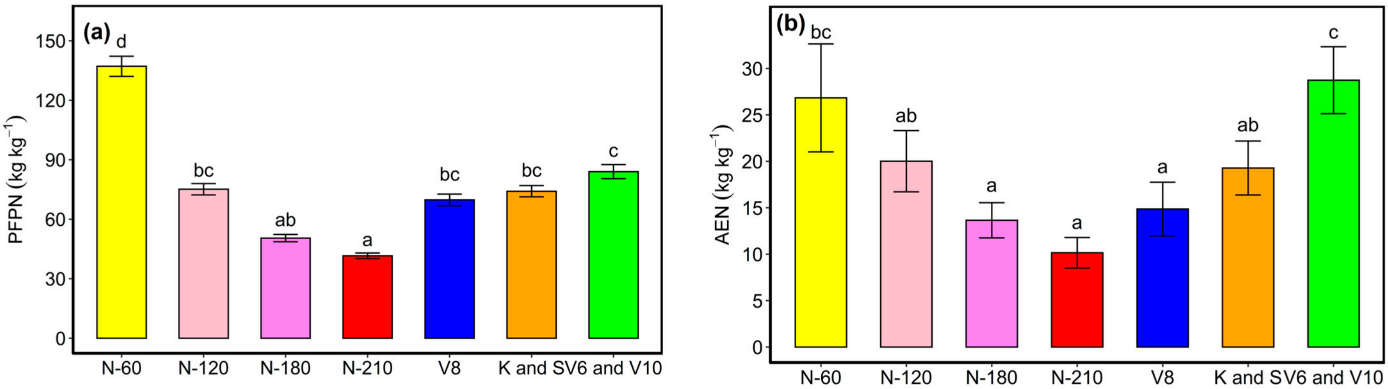

Figure 4. Average PFPN (**a**) and AEN (**b**) of different N rates and application timing across the districts; (mean ± SE). Different letters above a bar denote significant differences between the treatments (post hoc Tukey test, $p < 0.05$).

Among the different N rates, average PFPN was observed to be highest with N-60 (137 ± 6 kg kg $^{-1}$), followed by N-120 (75 ± 3 kg kg $^{-1}$), N-180 (51 ± 2 kg kg $^{-1}$) and N-210 (41 ± 2 kg kg $^{-1}$) (Figure 4). Similarly, among the three N timings, the highest PFPN was observed with N top-dressing at V6 & V10 (84 ± 4 kg kg $^{-1}$), followed by knee-height and shoulder-height (74 ± 3 kg kg $^{-1}$) and V8 stages (69 ± 3 kg kg $^{-1}$). For different N rates, average AEN was observed to be highest with N-60 (42 ± 5 kg kg $^{-1}$), followed by N-120 (28 ± 3 kg kg $^{-1}$), N-180 (17 ± 2 kg kg $^{-1}$) and N-210 (14 ± 2 kg kg $^{-1}$). Moreover, for N timing, average AEN was observed to be highest with N top-dressing at V6 & V10 (33 ± 3 kg kg $^{-1}$), followed by knee-height and shoulder-height (K & S, 26 ± 3 kg kg $^{-1}$) and V8 stages (23 ± 2 kg $^{-1}$).

3.4. Fertilizer BMPs and Farmers' Practice from Field Demonstrations

3.4.1. Fertilizer Management Practice by Farmers

Across the study districts, the average amount of nitrogen (N), phosphorus (P) and potassium (K) fertilizer applied by farmers was in lower quantities compared to the recommended rate of 120:60:40 kg N:P_2O_5:K_2O ha^{-1} for maize (Figure 5). The average N fertilizer used by farmers was 41 kg ha^{-1}, ranging from 0 to 130 kg ha^{-1} across the districts. The average P and K fertilizer used by farmers in the form of DAP and MOP was 36 kg ha^{-1} (ranging from 0 to 128 kg ha^{-1}) and 18 kg ha^{-1} (ranging from 0 to 74 kg ha^{-1}), respectively. Farmers from Doti did not apply fertilizer in the maize fields. The highest amount of N, P and K fertilizer was used by farmers from the Kavre district (Figure 5). The rate of NPK fertilizer used by farmers in 2018 and 2019 showed minimal variations across the districts (Figure S4).

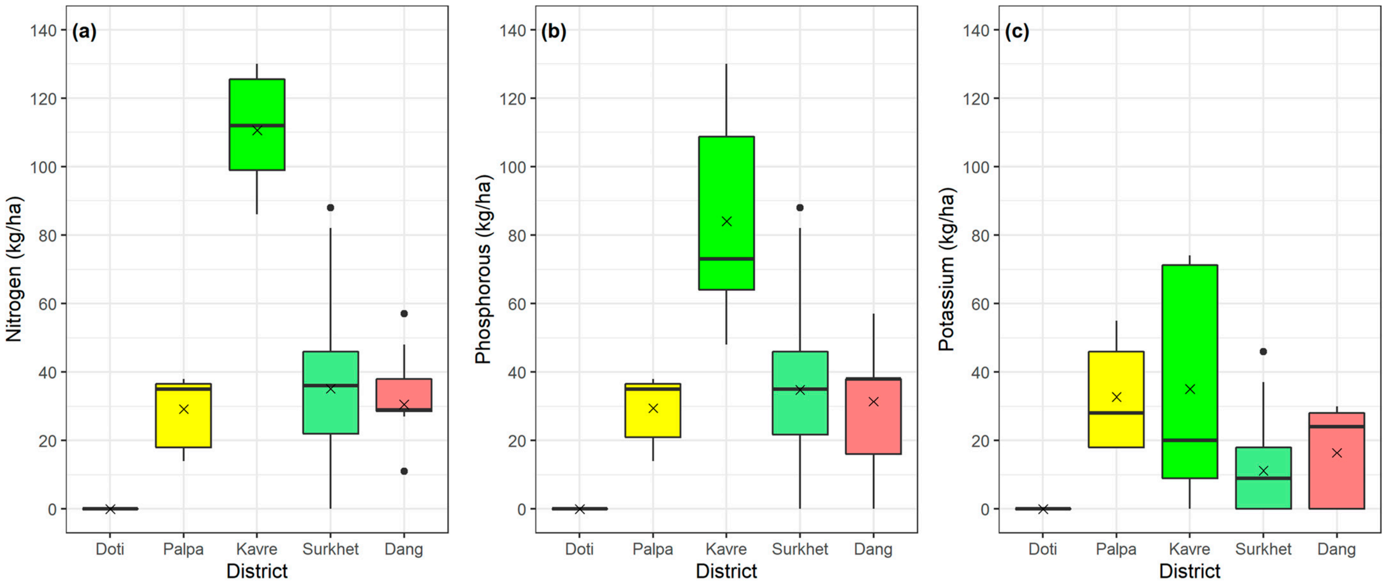

Figure 5. The average rate of N (**a**), P (**b**) and K (**c**) fertilizers used by farmers in maize across the districts. The sign (×) in the middle of the box plot refers to the average amount of fertilizer applied by farmers.

3.4.2. Yield Benefit from BMPs

Both BMPs (urea top-dressing at V6 & V10 and UDP) demonstrated significant agronomic benefits across the five mid-hills districts (Surkhet, Dang, Doti, Palpa and Kavre) (Table 3). Urea top-dressing at V6 and V10 increased maize yields by an average of 33% (8.7 t ha^{-1}) compared to existing farmers' practices (5.8 t ha^{-1}). Similarly, the application of urea briquette with deep placement (UDP) enhanced maize yields by 34% (8.8 t ha^{-1}) compared to FP across the districts (Table 3).

Table 3. Effect of fertilizer BMPs on maize yield in demonstration plots over two years (2018 and 2019; mean ± SE). Different letters in the table represent significant differences between treatments in average maize yield (post hoc Tukey test, $p < 0.05$).

Districts	Year 2018		Year 2019			Aggregated Year			Yield Gap (V6 & V10)
	FP	V6 &V10	FP	V6 &V10	UDP	FP	V6 &V10	UDP	
Dang	6.2 ± 2.0 a	8.6 ± 1.9 b	6.4 ± 2.6 a	8.6 ± 2.1 b	8.2 ± 1.8 b	6.3 ± 2.5 a	8.6 ± 2.0 b	8.2 ± 1.8 b	2.3
Surkhet	5.3 ± 1.8 a	8.7 ± 1.7 b	5.7 ± 1.1 a	9.3 ± 2.3 b	10.3 ± 2.5 b	5.5 ± 1.7 a	10.0 ± 2.1 b	10.3 ± 2.5 b	3.5
Doti	4.9 ± 1.6 a	8.0 ± 2.0 b	4.5 ± 0.3 a	8.0 ± 1.1 b	8.1 ± 0.7 b	4.7 ± 1.4 a	8.0 ± 2.0 b	8.1 ± 0.7 b	3.3
Palpa	5.0 ± 1.5 a	7.7 ± 1.6 b	5.1 ± 1.4 a	8.8 ± 1.2 b	8.4 ± 1.8 b	5.1 ± 1.5 a	8.2 ± 1.4 b	8.4 ± 1.8 b	3.1
Kavre	7.6 ± 2.1 a	9.2 ± 0.6 a	8.0 ± 1.5 a	6.4 ± 0.7 a	8.8 ± 1.0 a	7.8 ± 1.8 a	9.0 ± 1.0 a	8.8 ± 1.0 a	1.2
Average	5.8 ± 1.9 a	8.6 ± 1.8 b	5.9 ± 1.9 a	8.5 ± 1.9 b	8.8 ± 2.0 b	5.8 ± 1.9 a	8.7 ± 1.8 b	8.8 ± 2.0 b	3.0

3.4.3. Economic Benefit from BMPs

Both fertilizer BMPs (urea top-dressing at V6 & V10 and UDP) showed higher economic benefits compared to the control, N omissions, and existing farmers' practices (Table 4). Urea top-dressing at the V6 & V10 stage increased the gross margin by 39% (USD 1520) compared to farmers' practices (USD 925). Similarly, the application of UDP raised the gross margin by 40% (USD 1535) compared to FP.

Table 4. Average gross margin of nitrogen fertilizer BMPs (V6 & V10 and UDP) across the districts from trials and demonstrations.

Parameters	CK	N0	FP	UDP	V6 & V10
Yield (kg ha^{-1})	5670	6570	5800	8800	8750
Price (USD per kg)	0.23	0.23	0.23	0.23	0.23
Value of production (USD)	1289	1493	1318	2000	1989
Production cost (USD)	314	421	393	465	469
Gross margin (USD)	975	1072	925	1535	1520

4. Discussion

4.1. Grain Yields

Nitrogen fertilizer was responsive to maize compared to phosphorous and potassium across the trial sites (Figure 2a), underscoring nitrogen as the most limiting nutrient for maize growth and development, aligning with previous studies in Nepal [9,34,35]. Optimizing nitrogen fertilizer rate is crucial to improve NUE, increase yields, reduce production cost and increase farm profitability. In our study, maize yield increased with N rates up to 120–180 kg ha^{-1}, after which yields began to decline. The application of higher rates (210 kg N ha^{-1}) in these areas reduced yields while raising production costs and environmental costs. This is possibly due to the reason that the excessive nitrogen promotes plant height and vegetative growth, delaying physiological maturity and ultimately affecting grain yields [36]. In line with our studies, Dhakal et al. [9] reported optimal maize yields with N applications between 120 and 180 kg ha^{-1}, and an N rate beyond this rate (240 kg N ha^{-1}) reduced maize yield in Surkhet. Similarly, a study in Dang identified 143 kg ha^{-1} as the optimal rate based on the real-time N application using a leaf color chart (LCC) and green seeker (NDVI) [37]. Another study conducted in Lalitpur found that applying N rates up to 210 kg ha^{-1} resulted in the highest maize grain yield [38]. These results indicate that optimum N rates vary by agro-ecological zone, climate, variety, irrigation status and soil types, making site-specific nitrogen management crucial to improve NUE and yields [39].

Given that nitrogen can be lost from maize fields through various pathways, it is crucial to identify the appropriate timing of N application as synchronized with plant nutrient demand to reduce losses and enhance maize yields [18,40]. In Nepal, the recommended practice is to top-dress urea when maize reaches the knee-height and shoulder- height stages. However, variations in farmers' interpretations of these growth stages can result in mismatch of application timing. Considering the physiological crop stages, our study found that urea top-dressing at the V6 & V10 leaf stages increased maize yields by 25% compared to conventional practices. Similarly, a previous study [41] reported that N top-dressing at the V6 stage significantly enhanced NUE and maize production. Another study reported that top-dressing nitrogen at the V5 and V10 stages resulted in higher yields [42]. During stage V5-V6, maize undergoes rapid vegetative growth, while at the V10 stage there is an active nutrient translocation to support kernel development. In another study [19], N top-dressed at five different maize growth stages (V4, V6, V8, V10 and V12) showed maximum N uptake and higher maize yield during the V10 stage. Hence, applying N fertilizer between V6 and V10 growth stages, the critical periods for meeting high N demand, ensures efficient utilization and minimizes losses in maize fields.

In addition to the effect of N fertilizer treatments, site characteristics across the trial's location also showed significant variation in maize yields (Figure 2d). To explore whether the soil chemical properties (pH, OM, total soil N, available P and available K) across the trial locations influenced these yields, we clustered the yield data into three groups (k = 3) that fall within the range of each cluster mean and plotted each group against the soil chemical properties to assess their relationship. However, we found no significant relationship between soil fertility levels and clustered maize yields for each of the treatments (Figure S2). This was also further confirmed by linear regression, where no significant relationship was observed between soil properties and yields in control plots not receiving fertilizer (Figure S5). Moreover, the values of soil chemical properties across the trial sites were within the optimal range required for maize growth and development, potentially reducing yield variation (Table 1). Moreover, soil biological properties might have influenced the yields across the sites. However, these properties were not assessed in terms of how the activities of microorganisms could play a significant role in the decomposition and mineralization process, converting organic nutrients into inorganic plant available form (NH^{4+} or NO^{3-}) and thereby affecting maize productivity [43].

Temperature and rainfall are other key variables influencing maize productivity [44,45]. In our study, cumulative precipitation during the maize growing period was slightly higher in Dang (1509 mm) compared to Surkhet (1412 mm). However, average min and max temperatures were higher in Surkhet (21 °C and 32 °C) than in Dang (19.2 °C and 30.3 °C) (Figure 1). Higher maize yield across the trial sites in Surkhet relative to Dang could possibly be due to the higher average temperature in Surkhet, corroborated by previous studies from Nepal [45,46]. Higher average temperatures can enhance photosynthetic activity and the mineralization rate, converting organic nitrogen into available forms (nitrate or ammonium), which could positively affect yields. Maize was cultivated during the summer monsoon season, where heavier rainfall in Dang sites may have reduced yields through nutrient losses via leaching and surface run-off. In accordance with this, Poudel et al. [45] reported that each additional mm of rainfall during the monsoon could decrease maize yield by 0.06 kg ha^{-1} in Nepal. However, the impacts of temperature and rainfall on yields can vary depending on the crop growth stages and site characteristics.

4.2. Nitrogen Use Effeceincy (NUE)

The partial factor productivity of N (PFPN) and agronomic efficiency of N (AEN) are two critical components under NUE where PFPN measures crop yield produced per unit of N applied, while AEN represents the increase in crop yield per unit of N applied compared to systems without N addition [47]. PFPN and AEN guide farmers and agri-entrepreneurs in making decisions on whether to apply additional nitrogen to maximize marketable yields. In our study, both PFPN and AEN decreased with increasing N rate, which is corroborated by previous studies [9,35]. At the optimal N rate of 120 kg N ha^{-1}, nitrogen top-dressing at the V6 & V10 stages increased PFPN by 12% and 18% compared to top-dressing at the knee-height and shoulder-height (K & S) and V8 stages, respectively (Figure 4a). Similarly, AEN increased by 21% and 30% with N top-dressing at the V6 & V10 stages, compared to K & S and V8 stages, respectively (Figure 4b). This result indicates that switching nitrogen top-dressing from conventional practices to V6 & V10 stages can synchronize N supply with maize N demand, thereby increasing NUE and reducing N losses to the environment through leaching and gaseous emissions [18,20].

4.3. Fertilizer BMPs and Farmers' Practices

Fertilizer application at 120:60:40 kg NKP ha^{-1}, with nitrogen top-dressed in two equal splits at the V6 & V10 stages, showed superior yield effects (Figure 2c) and was demonstrated as a fertilizer BMP in farmers' fields to compare its yield and benefits against traditional practice. Farmers across the districts applied an average of 41 kg N, 36 kg P and 18 kg K per hectare, which was 65%, 40% and 55% lower, respectively, than the recommended dose of 120:60:40 kg NKP ha^{-1} (Figure 5). This insufficient fertilizer use has resulted in an average maize yield of 5.8 t ha^{-1} (ranging from 5.1 to 7.8 t ha^{-1}) (Table 3). Our study demonstrated that fertilizer BMPs, integrating balanced NPK fertilization with the 4Rs principle, have the potential to reduce the maize yield gap (Table 3) and increase farmers' profitability (Table 4). For instance, urea topdressing at V6 & V10 stages can reduce the average maize yield gap by 3.0 t ha^{-1} (ranging from 1.2 to 3.5 t ha^{-1}) across the districts (Table 3). Moreover, these BMPs increased the gross margin by 10% compared to conventional top-dressing practices at knee-height and shoulder-height stages and by 39% compared to farmers' practices (FPs). The increase in gross margin was attributed to higher grain yields with the use of BMPs. Though the cost of agri-input, particularly fertilizer, was lower in farmers' practices compared to BMPs, the higher yields achieved with BMPs offset these costs, resulting in greater profits (Table 4). Based on these agronomic, economic and environmental benefits, N top-dressing at V6 & V10 stages has been validated and endorsed by government and the Nepal Agricultural Research Council (NARC) as a maize fertilizer BMP. In a recent study, Khanal et al. [48] emphasized the pivotal role of managing nitrogenous fertilizer for ensuring food security across Asia, including Nepal. Therefore, our findings on maize fertilizer BMPs, based on the 4Rs principle, could be a promising approach to enhancing NUE (Figure 4), maize productivity (Table 3) and farm profitability (Table 4), supporting the hypothesis and aligning with the study conducted by Jat et al. [28]. Moreover, due to recurring shortages of subsidized fertilizer, it is crucial to test and promote alternative enhanced efficiency N fertilizers (EENFs). Findings from our study suggesting promoting urea briquette with deep placement technology (UDP) to reduce N inputs and enhance NUE [25], increase yields (Table 3) and boost farm income (Table 4), with minimal environmental impact, are corroborated by several previous studies [24,49–51]. In this study, deep placement of urea briquette (UDP) demonstrated the potential to reduce yield gaps, which ranged from 1.2 to 4.5 t ha^{-1} (Table 3). When urea briquettes are deep-placed in subsurface soils, nitrogen is retained in the plant's root zone for a prolonged period, allowing the plant to absorb N as needed based on its physiological requirements and boosting yield [49]. Higher profits are due to single time applications of UDP with reduced N, which saves fertilizer and labor costs compared to multiple split applications of regular urea [23,24]. Given the agronomic, economic and environmental benefits of using these fertilizer BMPs using the 4Rs and UDP, it is crucial to ensure the timely availability of fertilizer with easy access for farmers, involving both the public and private sectors [7], along with effective extension support to adopt these BMPs by farmers. In a recent study, farmers who participated in the demonstration and attended farmer field days were more likely to adopt BMPs, balance fertilization and apply fertilizer at the right rate and time [52].

5. Conclusions

This study demonstrates that fertilizer BMPs utilizing the 4Rs principle can significantly enhance maize yield, NUE and farm profitability. An optimum nitrogen rate of 120–180 kg N ha^{-1} was identified across the study areas, with urea top-dressing at V6 & V10 stages significantly enhancing maize yield. This underscores the importance of optimizing both the rate and timing of nitrogen fertilizer application to synchronize N supply with plant demand and maximize yields. As these practices are already endorsed by the government of Nepal as maize BMPs, it is recommended to promote and scale them at the farm level from local governments and relevant stakeholders through effective extension services including training, demonstrations and farmer school in order to reach a large number of farmers. It is also suggested to promote BMPs across other districts with varied agro-ecological zones in Nepal through research and extension efforts. This approach will support the government in making policy decisions regarding fertilizer imports and effectively planning the distribution process based on the specific fertilizer demands of various agro-ecologies. Across the districts, insufficient fertilizer uses by farmers led to lower yields. Promoting urea briquettes, which can be applied with 25% less nitrogen input without compromising yields, can help meet crop nitrogen requirements and close the existing yield gap. Moreover, policy support for private sectors in urea briquette production and distribution could foster its wider availability and adoption among farmers. Both BMPs (urea topdressing at V6 & V10 and UDP) play a pivotal role in achieving the sustainable development goals (SDGs), particularly SDG 2 (zero hunger) and SDG 13 (climate action), by promoting climate-resilient sustainable agriculture and enhancing food security.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/nitrogen6010007/s1, Figure S1: Map of the study area; Description S1: Brief description of soil analysis; Figure S2: Number of clusters for maize yield for all treatments; Figure S3: PFPN and AEN disaggregated by districts; Figure S4: Farmers' fertilizer management practices (2018 and 2019); Figure S5: Relationship between soil chemical properties and maize yields plotted in the control plot; Table S1: Description of production cost and gross margin.

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