Experimental Agriculture (2022), vol. 58, e14, 1–16
doi:10.1017/S0014479722000060

CAMBRIDGE
UNIVERSITY PRESS

RESEARCH ARTICLE

Enhanced-efficiency nitrogen fertilizer boosts cauliflower productivity and farmers' income: Multi-location and multi-year field trials across Nepal

Naba Raj Pandit[1,*], Yam Kanta Gaihre[1,2], Shriniwas Gautam[3], Shashish Maharjan[1], Shree Prasad Vista[4] and Dyutiman Choudhary[1]

[1]International Maize and Wheat Improvement Center (CIMMYT), P.O. Box 5186, Lalitpur, Nepal, [2]International Fertilizer Development Center (IFDC), Lalitpur, Nepal, [3]Pulte Institute for Global Development, University of Notre Dame, Indiana, USA and [4]National Soil Science Research Center (NSSRC), Nepal Agricultural Research Council (NARC), Lalitpur, Nepal
*Corresponding author. Email: N.PANDIT@cgiar.org

(Received 23 July 2021; revised 15 December 2021; accepted 11 February 2022)

Summary

Enhanced-efficiency nitrogen (N) fertilizers (EENFs) such as slow-release polymer-coated urea (PCU) and deep placement of urea briquettes (UBs) improve nitrogen use efficiency (NUE) by reducing N losses and increasing nitrogen uptake by plants. Multilocation field trials (81) with cauliflower were conducted across two agroecological regions covering seven districts during two crop-growing seasons between 2018 and 2020 to assess the potential of three EENFs, i.e., PCU, sulphur-coated urea (SCU) and UB for increasing curd yields, agronomic NUE (AE_N) and economic benefits over conventional urea (CU). Results were compared with farmers' current nutrient management practice (FP): applying CU at 58.5 kg N ha^{-1} (ranging from 33 to 88 kg N ha^{-1}). The N rates in three EENF treatments were 33% lower (100 kg N ha^{-1}), considering their higher N use efficiency, than for CU (150 kg N ha^{-1}). We hypothesize that EENFs produce similar or even higher yields compared with CU. For both years, all three EENFs resulted in significantly ($p < 0.05$) higher curd yields than CU (36.7 ± 1.1 t ha^{-1}). PCU, SCU and UB increased yields by 21, 21 and 24% over those for CU. The yield increment was much higher (PCU, 44%; SCU, 43%; UB, 46%) than for FP. Similarly, PCU, SCU and UB increased the partial factor productivity of N (PFP_N) by 91, 90 and 94% and the AE_N by 133, 129 and 138%, respectively, compared with CU. The gross margins of all three EENFs were similar: an average 25% more than with CU and 51% more than with FP. These results suggest that EENFs could help increase productivity and farmer income while considerably reducing N input, compared to use of CU. The government of Nepal should promote these EENFs by removing barriers to access for the associated fertilizers and foster their use through extension.

Keywords: Polymer-coated urea; Sulphur-coated urea; Urea briquette; Nitrogen use efficiency; Vegetable productivity; Nepal

Introduction

Cauliflower (*Brassica oleracea L.*var. *botrytis*) is a popular and economically important winter vegetable grown on more than 35,700 ha in Nepal, or almost 13% of vegetable crop area, with an average yield of 16 t ha^{-1} (MoALD, 2019). Although national production of vegetables, including cauliflower, is increasing, their productivity is low and significant imports are needed to meet domestic demand (Ojha, 2016). Lower cauliflower productivity is associated mainly with poor on-farm nutrient management, such as unbalanced and inefficient fertilization (Belbase and Bc, 2020; Neupane *et al.*, 2020).

Nepali farmers' fertilizer use is skewed towards excessive nitrogen (N) applications, with low or negligible use of secondary nutrients and micronutrients (Baral *et al.*, 2020), resulting in reduced nitrogen use efficiency (NUE) and large N losses to the environment through leaching, surface run off, volatilization, nitrification and denitrification (Gaihre *et al.*, 2015; Wang *et al.*, 2020). Besides affecting crop yields, such practices reduce soil fertility and help explain the wide gap between attainable yields and actual farm yields (Devkota *et al.*, 2018; Shrestha *et al.*, 2016).

Previous studies have cited N among the most limiting nutrients for crop productivity (Dhakal *et al.*, 2020; Shrestha and Maskey, 2005). In Nepal, farmers use conventional urea (CU) as a N source, which is associated with lower NUE (20–35%), reducing crop productivity and farm profits (Naz and Sulaiman, 2016). Lower NUE, along with possible reduced soil fertility and crops yields, is also associated with the application of fertilizers at fixed rates across different soil types and agro-ecologies, as well as inappropriate timing and inefficient application. Therefore, it is critical to find strategies to improve NUE and crop productivity. Following the 4Rs (right source, right rate, right time and right placement) for fertilizer use has been shown to improve crop productivity and NUE (Jones, 2021; Snyder, 2017) and could also work for vegetable farmers in Nepal.

Previous studies have shown that enhanced efficiency nitrogen fertilizers (EENFs), including slow and controlled release fertilizers and coated fertilizers, can improve NUE, allowing farmers to use much less fertilizer with no yield penalty and reduce N losses to the environment (Chen *et al.*, 2008; Gaihre *et al.*, 2015), contributing to sustainable development goals (Zhang *et al.*, 2015). Polymer- and sulfur-coated fertilizers (polymer-coated urea (PCU) and sulfur-coated urea (SCU)) enable the slow release of the fertilizer, i.e., the rate of dissolution and N availability is based on the plant's physiological requirement over a cropping period (Morgan *et al.*, 2009; Trenkel, 1997; Van Eerd *et al.*, 2017). In addition to agronomic and environmental benefits, EENFs are economically viable because they can be applied only once, saving time and labour compared with multiple, split applications of granular urea (Simonne and Hutchinson, 2005). Furthermore, the higher productivity of vegetables fertilized using EENF can offset the higher costs of PCU and SCU (Simonne and Hutchinson, 2005; Wang *et al.*, 2020). Several previous studies have documented the beneficial effects of EENF over conventional granular urea in saving N (Trenkel, 2010) and increasing vegetable productivity and farm profitability (Guertal, 2009; Sikora *et al.*, 2020; Van Eerd *et al.*, 2017; Wang *et al.*, 2020). Wang *et al.* (2020) reported that PCU applied at 31% less N increased winter chives yields by 37% over yields of chives grown with CU (100% N).

Another promising technique is applying fertilizer sub-surface or in the plant root zone, commonly called urea deep placement (UDP). For ease of deep placement, prilled or granular urea is compressed to a large granule (1–3 g) called a urea briquette (UB). The briquettes are placed 5–10 cm below soil surface and increase NUE, crop productivity and farm profitability over use of conventional granular urea (Agyin-Birikorang *et al.*, 2018; Chen *et al.*, 2020; Gaihre *et al.*, 2015; Pooniya *et al.*, 2018; Wang *et al.*, 2020). Placement of UB in the root zone helps to retain N longer and slow its release, making the nutrient continuously available as and when needed by crops (Agyin-Birikorang *et al.*, 2018; Baral *et al.*, 2020). In general, deep placement of UB with 20–35% less nitrogen maintained (Agyin-Birikorang *et al.*, 2018; Baral *et al.*, 2020) or increased crop yield by 25%, compared with conventional application of urea (Derrick *et al.*, 2017). These results suggest that yield increments with UB were not consistent across crops and sites.

Most previous studies have shown the potential of EENFs such as PCU, SCU and UB for cereal grain production, with few studies focusing on vegetable crops (Simonne and Hutchinson, 2005) or the effects of EENF on yields and NUE in Cole crops, particularly cauliflower (Van Eerd *et al.*, 2017). In this study, for the first time in Nepal, three different EENF products were tested for their agronomic and economic effects on cauliflower productivity. We assessed the potential of three EENFs (PCU, SCU and UB) to improve agronomic NUE, cauliflower productivity and farm profitability, using data from multilocation trials covering different agroecological zones and districts over two cropping seasons between 2018 and 2020. We hypothesized that the use of EENF increases agronomic NUE, curd yield and farmers' income, compared with CU and farmers' current nutrient management practices (FP).

Material and Methods

Site description and weather conditions

Field trials were conducted during 2018–2020 across seven districts; five in the Mid-hills (Dang, Palpa, Doti, Kavre and Surkhet) with average elevations ranging from 557 to 2512 m above sea level (masl) and subtropical climates and two in the Terai (Bardiya and Kailali) with average elevations from 112 to 117 masl and tropical climates (Fig. S1). The main cropping patterns are cauliflower–wheat–rice in the Terai and cauliflower–maize in the Mid-hills.

In the first year (November 2018 to March 2019), average minimum and maximum temperatures during the growing period were 11.0 °C (ranges from 6.7 to 14.7 °C) and 22.7 °C (ranges from 17.3 to 27.2 °C), respectively, across the districts. Similarly, in the second year (November 2019 to March 2020), average minimum and maximum temperatures were 13.2 °C (ranges from 8.8 to 16 °C) and 23.6 °C (ranges from 17.5 to 27.2 °C), respectively (Fig. S2). Average total rainfall across the districts was 120 ± 42 mm (ranging from 76 to 201 mm) and 181 ± 6 mm (ranging from 76 to 201 mm) during first and second year, respectively. Both temperatures and rainfall were moderate in Doti and Kavre and high in for other districts (Fig. S2)

Soil physicochemical properties

Triplicate soil samples were collected from each plot at a depth of 10 cm and pooled into a composite sample for each plot. Each sample was analysed for soil pH, organic matter (OM), texture, total N, and available P_2O_5 and K_2O, using visible-near-infrared diffuse reflectance spectroscopy (VisNIR-DRS) (Table 1). About 20% of the samples were analysed using wet chemistry to calibrate, build a partial least square regression (PLSR) model and determine the soil physiochemical properties through spectroscopy.

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 Walkley and Black (1934). Total N was analysed through Kjeldahl's method, in which samples are digested with sulphuric acid, distilled into a boric acid solution, following the titration of borate anions with standardized hydrochloric acid, to calculate the nitrogen content. Available P was determined through a modified Olsen's bicarbonate method, in which phosphate was extracted from the soil using a 0.5 N sodium bicarbonate solution adjusted to pH 8.5. The complex formed by the reaction between desorbed phosphate ions and molybdate was reduced using ascorbic acid to form a blue colour and the absorbance of the solution was measured at 880 nm using a spectrophotometer (Olsen and Sommers, 1982). Available K was determined using the neutral ammonium acetate method, where potassium is extracted from the soil with an ammonium acetate solution at 1:10 (soil: extractant ratio) and measured by a flame photometer. Soil texture was analysed using the hydrometer method (Bouyoucos, 1936), and the textural class was determined based on the USA Department of Agriculture (USDA) classification system. Soils were classified as silt loam and moderately acidic (pH ranging from 5.8 to 6.9). OM ranged from 1.5 to 3.4%, total N from 0.09 to 0.19%, available P_2O_5 from 33.9 to 89.3 mg kg^{-1} and available K_2O from 79.1 to 234.3 mg kg^{-1} (Table 1).

Experimental set-up and cultivation practices

A total of 81 field trials were established across 7 districts in 2 agroecological regions, the Mid-hills (subtropical climate) and Terai (tropical climate), during November-February 2018 ($n = 49$) and 2019 ($n = 32$). Twelve field trials were established in Dang, 14 in Palpa, 12 in Doti, 9 in Kavre, 17 in Surkhet, 8 in Bardiya and 9 in Kailali. Trials were conducted with a farmer cooperative that

Table 1. Soil characterization across the study districts (mean ± SE)

	Texture (%)					OM	Total N	P_2O_5	K_2O
Districts	Sand	Silt	Clay	Textural Class[1]	pH	g kg^{-1}	g kg^{-1}	(mg kg^{-1})	(mg kg^{-1})
Maize trials									
Dang (n = 22)	42 ± 1	37 ± 1	21 ± 0	Loam	6.49 ± 0.05	25.53 ± 0.93	1.33 ± 0.05	48.94 ± 5.41	143.43 ± 11.37
Palpa (n = 8)	44 ± 2	41 ± 1	15 ± 1	Loam	6.51 ± 0.01	31.48 ± 2.02	1.48 ± 0.11	38.78 ± 8.29	234.31 ± 32.91
Doti (n = 6)	46 ± 1	38 ± 2	16 ± 1	Loam	6.31 ± 0.08	34.20 ± 2.34	1.91 ± 0.15	89.25 ± 18.62	144.75 ± 17.39
Kavre (n = 8)	45 ± 1	38 ± 1	17 ± 1	Loam	5.89 ± 0.02	15.88 ± 0.37	0.94 ± 0.04	66.51 ± 11.91	199.58 ± 24.01
Surkhet (n = 24)	40 ± 2	45 ± 1	15 ± 1	Loam	6.68 ± 0.08	28.12 ± 1.36	1.60 ± 0.08	82.77 ± 9.53	145.27 ± 11.70
Bardiya (n = 13)	40 ± 2	40 ± 1	20 ± 1	Loam	6.95 ± 0.10	19.01 ± 0.64	1.09 ± 0.04	33.91 ± 5.40	79.14 ± 6.88
Kailali (n = 15)	29 ± 3	48 ± 4	23 ± 2	Loam	6.73 ± 0.05	19.13 ± 0.65	1.17 ± 0.05	44.08 ± 4.17	88.28 ± 5.89
Analytical method	(Bouyoucos 1936)				H_2O	(Walkley and Black 1934)	Kjeldhal method	Modified Olsen bicarbonate	Flame photometric

distributes subsidized fertilizers to farmers. Within each cooperative, three farmers' field was selected randomly for the trials. In each trial, we set up five treatments, including the control (without fertilizer; CK) and CU, PCU (44% N, 90 days release; PUREKOTE^{TM}, Pursell Agri-Tech LLC, AL 35 150, USA), SCU (39% N, 13.8% S, Thiogro ES, Shell, Canada) and UB in a randomized complete block design with three replications in each cooperative. In the CU treatment, granular urea was applied at 150 kg N ha^{-1}, a rate considered optimum, based on the multilocation N rate field trials conducted across the study districts in 2017 (Fig. S3). Considering the higher N use efficiency of EENF (Agyin-Birikorang *et al.*, 2018; Baral *et al.*, 2020; Wang *et al.*, 2020), N rates in PCU, SCU and UB were reduced by 33% (100 kg N ha^{-1}), compared with CU. Phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied at the same rate for all the treatments (120:100 kg P_2O_5: K_2O ha^{-1}) in the form of diammonium phosphate (DAP) and muriate of potash (MOP). Treatment plots measured 13.5 m^2 (4.5 m × 3 m).

For land preparation, each plot was plowed two to three times with moldboard plow. Hybrid cauliflower varieties ('Snow Crown' in the Mid-hills and 'Snow Mystique' in the Terai) were planted at a spacing of 60 cm × 45 cm. The full dosage of DAP (120 kg P_2O_5 ha^{-1}), MOP (100 kg K_2O ha^{-1}) and micronutrients (Boron [1.7 kg ha^{-1}] in the form of Borax and Zinc [7 kg ha^{-1}] in the form of zinc sulphate) were applied equally in all treatment plots during planting at a depth of 5 cm and 5–7 cm apart from seedlings. In EENF treatments, a full dosage of PCU and SCU was applied at a depth of 5 cm and 5–7 cm apart and one UB (weigh 2.7 g each) per plant at a depth of 7–10 cm and 5–7 cm apart, as a basal application. In the CU treatment, granular urea was top dressed at a depth of 5 cm in two equal splits (30 and 50 days after plantation; Table 2). Hand weeding and earthing up (5 cm high) were carried out twice at 30 and 50 days after plantation. Blanching was performed to protect the curd from sunlight and improve texture or flavour by covering the curd with outer leaves and tying them with a twine or rubber band for 4–5 days. Irrigation, pest and disease management and other routine agronomic practices were performed as and when needed.

Farmer's nutrient management practices

To compare the yield benefits of EENFs over those resulting from farmers' traditional practices, we added the treatment 'farmers' nutrient management practices (FP).' To assess FP yields, fertilizer rates and profits, we conducted surveys ($n = 105$) and crop cuts ($n = 35$) in the fields of farmers located near experiment sites (one farmer per experiment). Farmers were interviewed using a structured questionnaire in 'open data kit' software. For crop-cuts, three quadrants of 1 m^2 = 3 m^2 in total were selected randomly from farms adjoining trial sites and harvested to record the yield (Fermont and Benson, 2011).

Farmers' fertilizer use varied across the districts. On average, N fertilizer use by farmers was 58.5 kg ha^{-1} (ranging from 33 to 88 kg N ha^{-1}), which is 70% less than the government's recommendation (RP) of 200:120:100 kg N P_2O_5 K_2O ha^{-1} (Figure 1). NPK rates in Dang and Palpa were lower than that in other districts. Similarly, the average application rates of P_2O_5 and K_2O were 43.5 kg ha^{-1} (ranging from 18 to 56 kg P_2O_5 ha^{-1}) and 22.8 kg ha^{-1} (ranging from 1 to 42 kg K_2O ha^{-1}), which is 64% and 77% less than the RP, respectively (Figure 1). NPK fertilizer rates for the Mid-hills and the Terai were similar (Figure 1).

Yield and nitrogen use efficiency (NUE)

Cauliflower was harvested from three quadrants of 1 m^2 (3 m^2 in total) in each treatment plot, when the curds had attained proper size and compactness. Harvesting was performed manually by cutting the stem 3–5 cm above soil surface, excluding the 50 cm border row. Marketable curd yield was measured after removing stem and leaves.

Table 2. Description of the treatments; enhanced efficiency nitrogen fertilizers (EENFs), i.e., sulphur-coated urea (SCU), polymer-coated urea (PCU) and urea briquette (UB) along with conventional urea (CU), control (CK) and farmers practices (FP) across seven districts for the year 2018 and 2019 (n = 81)

Fertilizer inputs	Treatment description					
	Control (CK)	Conventional urea (CU)	Sulphur-coated urea (SCU)	Polymer-coated urea (PCU)	Urea briquette (UB)	Farmer’s practice (FP)[3]
N (kg ha^{-1})	0	150	100	100	100	58.5
P_2O_5 (kg ha^{-1})	0	120	120	120	120	43.5
K_2O (kg ha^{-1})	0	100	100	100	100	22.8
Farm yard manure (FYM) (kg ha^{-1})	30 000	30 000	30 000	30 000	30 000	30 000
Boron (kg ha^{-1})	0	1.7	1.7	1.7	1.7	
Zinc (kg ha^{-1})	0	7	7	7	7	
Urea[1] (kg ha^{-1})	0	224	136	123	115	90.5
DAP[2] (kg ha^{-1})	0	261	261	261	261	94.5
MOP (kg ha^{-1})	0	167	167	167	167	38
Urea (g $plot^{-1}$)	0	302	184	167	156	
DAP (g $plot^{-1}$)	0	352	352	352	352	
MOP (g $plot^{-1}$)	0	225	225	225	225	
Farm yard manure (FYM) (g $plot^{-1}$)	40 500	40 500	40 500	40 500	40 500	
Borax (g $plot^{-1}$)	0	18.9	18.9	18.9	18.9	
Zinc sulphate (g $plot^{-1}$)	0	27	27	27	27	

[1] Urea applied in the form of CU and UB contains 46% N, SCU contains 39% N and 13% elemental sulphur and PCU contains 44% N.

[2] DAP contains 46% P_2O_5 and 18% N.

[3] Average use of NPK across the districts by farmers. Farmers practice treatment was included to compare the cauliflower yield across the districts compared with various N source treatments.

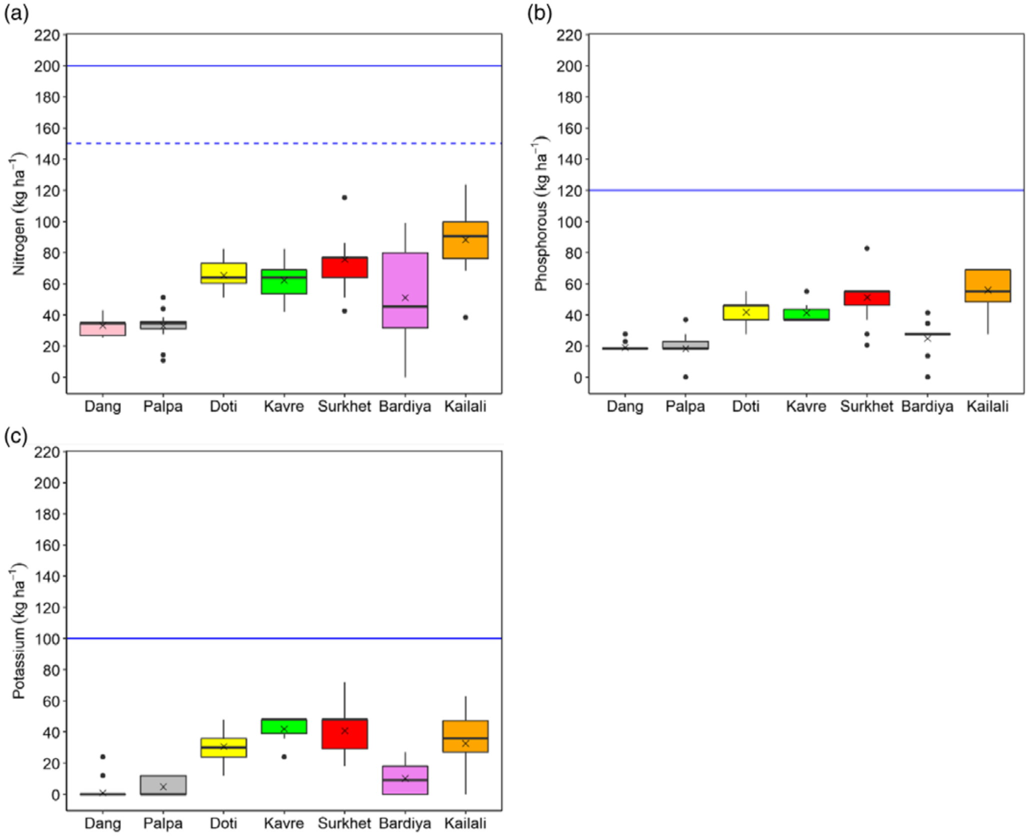

Figure 1. N (a), P (b) and K (c) fertilizer applied by farmers across the districts; Dang (n = 35), Palpa (n = 9), Doti (n = 12), Kavre (n = 6), Surkhet (n = 12), Bardiya (n = 15) and Kailali (n = 16). Sign (×) in the middle of the boxplot refer to the average amount of NPK fertilizers used by the farmers. Blue horizontal solid line in each figure (a, b & c) represents the existing blanket NPK fertilizers recommendation rate in Nepal. Dashed blue line in figure (a) represents the optimum N rate identified through the project across the district locations.

NUE was calculated as partial factor productivity ($\mathrm{PFP_N}$) and agronomic use efficiency of nitrogen ($\mathrm{AE_N}$) for all N source treatments (CU, PCU, SCU and UB) using the following equation:

$$\mathrm{PFP_N} = \mathrm{Y_N}/\mathrm{F_N},\ \text{kg cauliflower yield per kg N applied}$$

$$\mathrm{AE_N} = (\mathrm{Y_N} - \mathrm{Y_0})/\mathrm{F_N},\ \text{kg cauliflower yield increases per kg N applied}$$

where $\mathrm{Y_N}$ is the cauliflower yield with applied nitrogen (kg $\mathrm{ha^{-1}}$), $\mathrm{Y_0}$ is the cauliflower yield without fertilizer and $\mathrm{F_N}$ is the amount of N applied (kg $\mathrm{ha^{-1}}$).

Economic analysis

Cost–benefit analysis of EENFs (PCU, SCU and UB), CU and FP was performed based on data from field trials, crop cuts and surveys. Agronomic costs included costs of seed, fertilizer and labour required for fertilizer application and other agronomic practices (irrigation, weeding, pest management and harvest) (Table S1). The retail price of cauliflower was based on the local market price (USA$ 254 per ton). Gross margin (GM) was calculated as the differences between cauliflower sales and total variable costs (TVC) across districts (Pandit *et al.*, 2018).

Data analysis

Data were analysed using R statistical software, version 3.6.2 (R Core Team., 2019). A linear mixed effect model was applied using the 'lmer' function in the 'lme4' extension package to assess the fixed effects of N sources (treatments) on cauliflower yield, with location as a random factor (district site and agroecological region), fitted by the Restricted Maximum Likelihood (REML) (model I). A mixed model was used for district-level disaggregated analysis including municipalities (block) within each district. Variety was not included in the model together with N sources as a fixed factor, due to non-significant effect of variety on crop yields. In the mixed effect model, FP treatment was omitted for both aggregated and disaggregated trial data, as the observed yield response might be biased due to variation in farmers' crop management practices. We performed one-way fixed effect ANOVA to compare the cauliflower yields under FP with various N source plots, allowing comparisons of yield response as a function of source of nitrogen and fertilizer management practices (model II). Similarly, one factor ANOVA was used to assess the effect of different N on PFP_N and AE_N (model III). Significant differences between treatment means of cauliflower yield, PFP_N and AE_N were evaluated through a post hoc Tukey test ($p = 0.05$). Model checking was performed through basic diagnostic plots (Normal Q-Q and residuals plots). The differences between various treatments were significant at $p < 0.05$, unless stated otherwise. A multiple linear regression model was used to assess the effect of soil chemical properties (pH, OM, total N, available P and K [continuous variables]) on cauliflower productivity across the district locations (model IV). Models I, II, III and IV follow these equations and assumptions:

$$Y_{ijk} = \mu + \tau_i + \beta_j + \varepsilon_{ijk} \ldots \text{model I (linear mixed effect model)}$$

$$Y_{ik} = \mu + \tau_i + \varepsilon_{ik} \ldots \text{model II (linear one} - \text{way ANOVA model)}$$

$$Y_{jk} = \mu + \tau_j + \varepsilon_{jk} \ldots \text{model III (linear one} - \text{way ANOVA model)}$$

$$Y_{ijklm} = \beta_0 + \beta 1x_i + \beta 2x_j + \beta 3x_k + \beta 4x_l + \beta 5x_m + \varepsilon_{ijklm} \ldots \text{model IV (multiple linear regression)}$$

where

$\sum \tau_i = \sum \tau_j = 0$, i.e., τ_i and τ_j are the fixed effect coefficient for observations i and j (treatments) and the summation of all the parameters are zero.

$\beta_j \sim N(0, \sigma^2_\beta)$, i.e., β_j is the random effect coefficient for observation j (trial locations).

$\varepsilon_{ijklm} = \varepsilon_{ijk} = \varepsilon_{ik} = \varepsilon_{jk} \sim \text{NID}(0, \sigma^2)$; i.e., residuals are independent and normally distributed with constant variance.

Y_{ijk} represents the value of observed crop yield (response variable) in response to τ_i; i.e., fixed effect coefficient of treatments (CK, CU, SCU, PCU and UB), and β_j represents the random effect coefficient of trial locations across seven districts or two agroecologies. Y_{ik} represents the yield in response to treatments (τ_i), including FP, in the model. Y_{jk} represents the observed PFP_N and AE_N in response to four N source treatments (τ_j), i.e., CU, PCU, SCU and UB. μ represents the overall mean. K represents the number of replications in each model ($k = 1, 2 \ldots n$). Y_{ijklm} represents crop yield in response to a continuous regressor variable; i.e., x_i, x_j, x_k, x_l *and* x_m, denoting pH, OM, available P, K and total N *(i, j, k, l, m* $= 1, 2 \ldots n$*)*, with their corresponding slopes $\beta 1, \beta 2, \beta 3, \beta 4$ *and* $\beta 5$, respectively, and the intercept β_0.

Results

Curd yield

Cauliflower yield was significantly ($p < 0.05$) affected by both N source (Figure 2) and site (Figure 3). EENFs (PCU, SCU and UB) produced significantly higher cauliflower yield compared with CU and FP (Figure 2). PCU, SCU and UB increased cauliflower yield by 22% (47.1 ± 1.6 t ha^{-1}), 21% (46.7 ± 1.7 t ha^{-1}) and 24% (48.0 ± 1.6 t ha^{-1}) compared with CU (36.7 ± 1.1 t ha^{-1}),

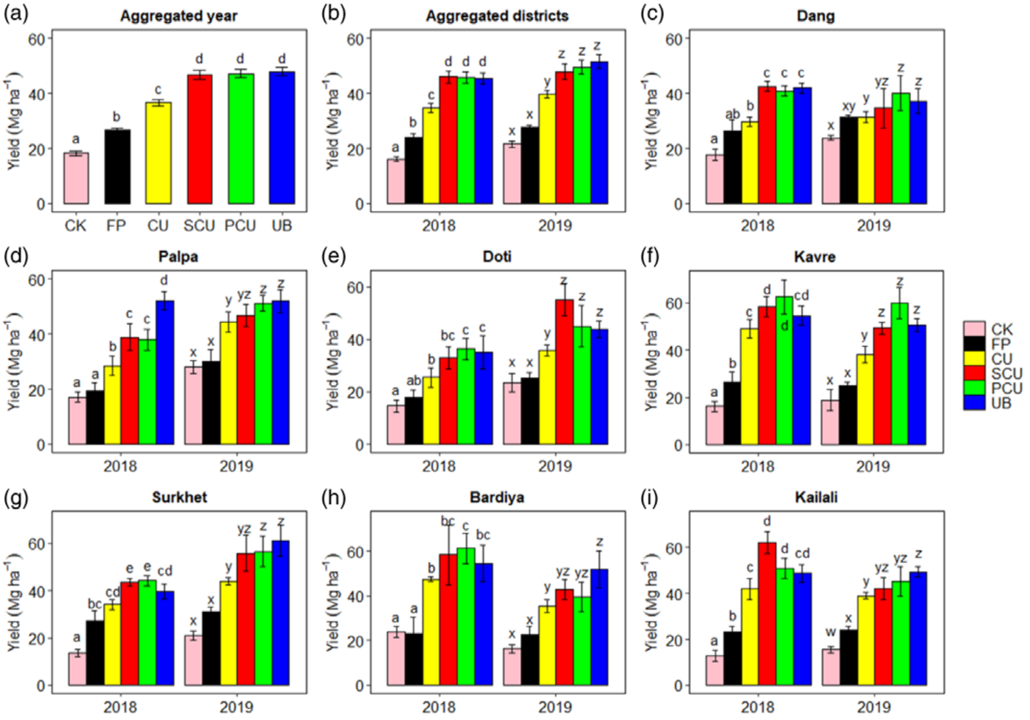

Figure 2. Cauliflower yield (mean ± SE) in response to enhanced efficiency nitrogen fertilizers (EENFs), i.e., polymer-coated urea (PCU), sulphur-coated urea (SCU) and urea briquette (UB) along with conventional urea (CU), control (CK) and farmers practices (FP) across the districts in the year 2018 and 2019. Different letters inside a bar and within a year represent significant difference between the treatments at 5% probability level (post hoc-Tukey test, $p < 0.05$).

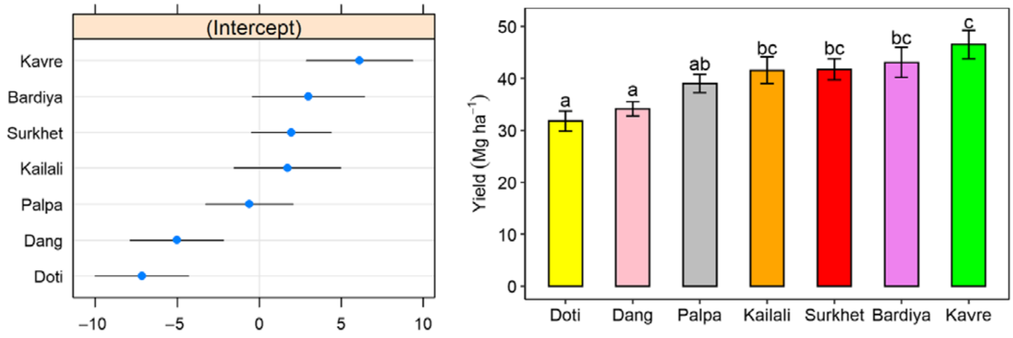

Figure 3. Location effect on cauliflower yield across the districts followed by mixed effect model (n = 81). Different letters inside a bar and within a year represents significant difference between the treatments at 5% probability level.

respectively (Figure 2.a). Similarly, PCU, SCU and UB increased cauliflower yield by 44, 43 and 46%, respectively, over FP (26.6 ± 0.7 t ha^{-1}). The use of the EENFs resulted in yields higher than those of CU and FP across agroecological regions, with a greater effect in the Terai than the Mid-hills (Fig. S4).

Table 3. Partial factor productivity of N (PFP$_N$) and agronomic N use efficiency (AE$_N$) across different N source treatments in 2018 and 2019 for aggregated and disaggregated districts in terai agroecological region. PFP$_N$ and AE$_N$ values are given as mean ± SE. Within a column and districts, means followed by different letters are significantly different at 5% probability level

		Year 2018		Year 2019		Aggregated year	
		PFP$_N$	AE$_N$	PFP$_N$	AE$_N$	PFP$_N$	AE$_N$
Location	N sources	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}
Aggregated districts							
	CU	232 ± 11a	125 ± 10a	268 ± 8a	124 ± 11a	246 ± 8a	124 ± 7a
	SCU	459 ± 22b	299 ± 22b	478 ± 27b	262 ± 23b	467 ± 17b	284 ± 18b
	PCU	456 ± 20b	296 ± 18b	495 ± 26b	279 ± 27b	471 ± 15b	289 ± 16b
	UB	453 ± 19b	293 ± 18b	515 ± 26b	299 ± 27b	478 ± 17b	295 ± 15b
Disaggregated districts in Terai							
Bardiya	CU	315 ± 7a	157 ± 12a	236 ± 20a	127 ± 32a	275 ± 18a	142 ± 17a
	SCU	582 ± 134b	344 ± 11b	427 ± 44b	264 ± 42b	504 ± 71b	304 ± 57b
	PCU	611 ± 69b	374 ± 55b	394 ± 65b	231 ± 57b	503 ± 60b	303 ± 45b
	UB	544 ± 81b	307 ± 61b	518 ± 81b	355 ± 70b	531 ± 53b	331 ± 44b
Kailali	CU	279 ± 30a	194 ± 35a	281 ± 15a	178 ± 20a	280 ± 20a	188 ± 23a
	SCU	620 ± 46b	492 ± 47b	420 ± 49b	265 ± 60ab	553 ± 47b	416 ± 51b
	PCU	508 ± 45b	380 ± 51b	452 ± 63b	297 ± 71b	489 ± 35b	342 ± 41b
	UB	486 ± 36b	359 ± 45b	494 ± 21b	338 ± 8b	489 ± 24b	352 ± 29b

Table 4. Partial factor productivity of N (PFP$_N$) and agronomic N use efficiency (AE$_N$) across different N source treatments in 2018 and 2019 for disaggregated districts in mid-hill agroecological region. PFP$_N$ and AE$_N$ values are given as mean ± SE. Within a column and districts, means followed by different letters are significantly different at 5% probability level

		Year 2018		Year 2019		Aggregated year	
		PFP$_N$	AE$_N$	PFP$_N$	AE$_N$	PFP$_N$	AE$_N$
Location	N sources	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}
Disaggregated districts in Mid-hill							
Doti	CU	169 ± 24a	72 ± 19a	238 ± 14a	79 ± 35a	186 ± 20a	74 ± 16a
	SCU	329 ± 41b	183 ± 44b	550 ± 60b	312 ± 62b	384 ± 43b	215 ± 39b
	PCU	363 ± 40b	218 ± 77b	449 ± 78b	211 ± 108ab	385 ± 36b	216 ± 29b
	UB	349 ± 61b	203 ± 55b	438 ± 30b	133 ± 15ab	371 ± 47b	202 ± 42b
Dang	CU	197 ± 10a	79 ± 8.9a	208 ± 13a	50 ± 16a	201 ± 8a	70 ± 9a
	SCU	424 ± 19b	248 ± 35b	345 ± 71b	108 ± 64ab	398 ± 27b	201 ± 36b
	PCU	407 ± 18b	231 ± 29b	400 ± 64b	162 ± 59b	405 ± 22b	208 ± 28b
	UB	419 ± 18b	243 ± 26b	371 ± 45b	133 ± 40b	403 ± 19b	206 ± 26b
Surkhet	CU	227 ± 14a	136 ± 12a	293 ± 11a	153 ± 30a	262 ± 11a	145 ± 11a
	SCU	435 ± 15b	299 ± 21b	557 ± 76b	281 ± 49b	500 ± 42b	325 ± 43b
	PCU	441 ± 20b	305 ± 19b	565 ± 63b	289 ± 46b	507 ± 37b	332 ± 35b
	UB	397 ± 31b	261 ± 27b	611 ± 65b	334 ± 47b	510 ± 45b	335 ± 40b
Palpa	CU	189 ± 24a	75 ± 16a	296 ± 24a	98 ± 16a	235 ± 22a	90 ± 16a
	SCU	387 ± 48b	216 ± 46b	467 ± 30b	348 ± 56b	421 ± 33b	203 ± 34b
	PCU	378 ± 37b	207 ± 14b	511 ± 28b	355 ± 55b	435 ± 29b	217 ± 27b
	UB	520 ± 32b	348 ± 43b	519 ± 42b	401 ± 60b	519 ± 25b	301 ± 31b
Kavre	CU	327 ± 45a	219 ± 24a	277 ± 8a	152 ± 27a	310 ± 18a	197 ± 20a
	SCU	582 ± 42bc	421 ± 42b	493 ± 23b	306 ± 23b	553 ± 31b	383 ± 34b
	PCU	624 ± 71c	463 ± 62b	598 ± 66b	412 ± 23b	616 ± 49b	446 ± 41b
	UB	480 ± 45b	385 ± 42b	505 ± 27b	318 ± 19b	532 ± 29b	366 ± 33b

Nitrogen use efficiencies

EENFs significantly increased PFP$_N$ and AE$_N$ over CU in both the Terai (Table 3) and the Mid-hills (Table 4) and with a comparable degree of increase among the three EENFs. On the average, PCU increased PFP$_N$ and AE$_N$ by 91% (ranging from 363 to 624 kg kg^{-1}) and 133% (ranging from

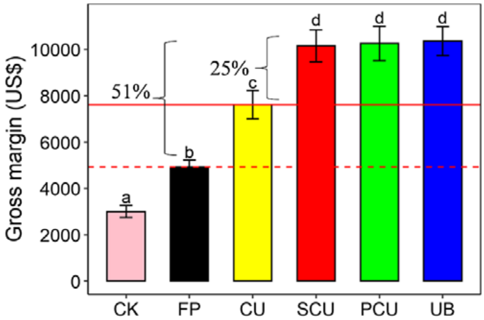

Figure 4. Average gross margin (mean ± SE) of different N source treatments across the districts ($n = 7$). Different letters inside a bar represent significant difference between the treatments at 5% probability level (post hoc-Tukey test, $p < 0.05$). Black and dashed lines inside graph are the lines representing GM values of CU and FP, respectively, and % represents the relative increment of GM with the use of enhanced efficiency nitrogen fertilizer (EENF), i.e., polymer-coated urea (PCU), sulphur-coated urea (SCU) and urea briquette (UB) over conventional urea (CU) and farmers practice (FP), respectively.

162 to 463 kg kg^{-1}) over CU, respectively (Tables 3 and 4). SCU increased PFP_N by 90% (ranging from 329 to 620 kg kg^{-1}) and AE_N by 129% (ranging from 183 to 492 kg kg^{-1}) over CU (ranging from 169 to 315 and 50 to 219 kg kg^{-1} for PFP_N and $AE_{N,}$ respectively). Similarly, UB increased PFP_N and AE_N by 94% (ranging from 371 to 611 kg kg^{-1}) and 138% (ranging from 133 to 401 kg kg^{-1}), over CU, respectively.

Economic return

GMs for EFNFs were at least 25% higher than for CU and 50% higher than with FP. Average GM per hectare was significantly ($p < 0.05$) higher for PCU (USA$ 10 258), SCU (USA$ 10 159) and UB (USA$10 363) than for CU (USA$ 7,618) or FP (USA$ 4,113) (Figure 4), and this difference was consistent across districts and agroecology (Table S1). GM along with their associated production cost for EENFs, CU and FP disaggregated by districts and agroecological region are shown in supplementary information (Table S1).

Discussion

Yield response across seven districts spread over two agroecological region over two-year period clearly illustrates the positive effect of all three EENFs in increasing cauliflower productivity while saving 33% of the N normally providing using urea fertilizer (Figure 2). There are very few studies that investigated the agronomic effects of these EEFNs on Cole crops and to the best of our knowledge there are no study, specifically on cauliflower. Thus, in this study, we discussed our agronomic result based on the literature broadly available on vegetable productivity to illustrate the mechanistic effect of EENFs on crop growth and productivity.

In our study, yield benefits of both PCU and SCU were 23% higher than with CU (Figure 2). In accordance with this, Wang *et al.* (2020) reported that PCU with 31% less N increased vegetable production (winter chives) by 37% compared with CU, although yield increases were not consistent across the reported studies. Some studies have reported no yield benefits in cabbage or tomato with the use of PCU instead of CU (Csizinszky, 1994; Van Eerd *et al.*, 2017), particularly when CU was applied in multiple splits synchronizing N supply with plant N demand (Guertal, 2009). Similarly, McArdle and McClurg (1986) reported no difference in tomato yield with the use of SCU over CU. In contrast, Brown *et al.* (1988) reported that the use of SCU at lower N rates significantly increased onion yields, over CU. This variable crop response may be due to the differing nutrient composition of SCU, which is used as a blanket term in many studies

(Guertal, 2009), and differences in CU treatments, such as single vs multiple split applications. Different nutrient composition and N release mechanisms in different SCU products may directly influence crop productivity. In our study, SCU contains 39% N and 13.8% sulphur, and there could be a synergistic effect of sulphur and nitrogen on cauliflower productivity, as reported in earlier studies (Liu *et al.*, 2020; Rossini *et al.*, 2018). Perveen *et al.* (2021) reported that PCU in combination with sulphur fertilization increased sunflower yield by 32% over CU, without sulphur addition. Considering the higher NUE resulting from use of these EENFs and an improved capacity to meet crop nutrient demands (Carson and Ozores-Hampton, 2012), N input with slow release N fertilizers such as PCU and SCU could be reduced by 25% (Carson and Ozores-Hampton, 2013) or even by as much as 50 to 75%, with the use of PCU, to maintain similar or even higher yields (Ransom, 2014). Improved vegetable productivity despite lower amounts of fertilizer results from the continuous availability of N, as PCU and SCU is encapsulated with a polymeric or resin layer that dissolves very slowly in water, thereby releasing N slowly and synchronizing N supply with plant demand (Guertal, 2009; Morgan *et al.*, 2009; Trenkel, 2010).

Use of UB with deep placement showed a similar degree of cauliflower productivity as with slow release N fertilizers (PCU and SCU) over CU. Increased cauliflower yield with UB could be due to a continuous supply of N in sub-surface, root-zone soil layers for prolonged periods, allowing uptake by the plant as and when required (Agyin-Birikorang *et al.*, 2018; Baral *et al.*, 2020). In addition, the precision application associated with UB could result in a uniform curd size, adding market value, so our study could contribute to future research about the effects of UB on vegetable productivity.

In addition to N fertilizer treatments, site characteristics caused significant ($p < 0.05$) variation in cauliflower productivity (Figure 3), possibly due to varied soil characteristics (Table 1) and other biophysical (temperature and rainfall) factors. Previous studies reported that vegetable productivity in response to slow release N fertilizers or EENFs varied greatly with soil type and temperature (Morgan *et al.*, 2009). In our study, soil chemical properties such as pH, OM, total N, available P_2O_5 and K_2O were not associated with significant variation in cauliflower productivity (Fig. S5). Moreover, the values for these soil chemical properties were within the range required for proper cauliflower growth (Table 1). Lower cauliflower productivity was observed at Doti and Dang and higher productivity at Kavre (Figure 3). In accordance with this, our previous study on maize in same district reduced crop productivity, which was possibly due to higher soil fertility (high soil OM, total N) that correlates negatively with fertilizer addition (Vanlauwe *et al.*, 2010). Furthermore, lower crop yields could be associated with lower rainfall at the site (Fig. S2), inducing water stress during critical growth periods. Higher crop productivity in Kavre could be due to moderate temperatures (minimum and maximum temperature of 6.7 ^{0}C and 19 ^{0}C, respectively) (Fig. S2), in a good range for effective photosynthetic activity and crop growth (Rodríguez *et al.*, 2015). In accordance with this, Ray and Mishra (2017) reported the optimum minimum and maximum temperature of 4.6 to 6.8 ˚C and 15.4 to 19 ˚C, respectively, for maintaining proper growth and development of cool season cauliflower.

Cauliflower yields were much higher for EENFs (an average increase of 11% compared with CU) than for FP, which features rates that are one-third of the RP (Figure 1), illustrating the potential of PCU, SCU and UB for reducing the current yield gap in cauliflower production in Nepal.

Agronomic nitrogen use efficiency (AE_N) is an important index to identify the agronomic potential of added fertilizers on crop productivity. In our study, use of all three EENFs resulted in higher PFP_N and AE_N than with CU across districts (Tables 3 and 4), which corroborated results of previous studies outside of Nepal (Drost *et al.*, 2002; Wang *et al.*, 2020). Wang *et al.* (2020) reported respective PFP_N and AE_N increases of 58% and 257%, with the use of PCU instead of CU. In general, NUE of CU is 20–35% and may be reduced dramatically from that, under poor conventional nitrogen management practices (Chen *et al.*, 2008; Naz and Sulaiman, 2016). Previous studies have shown that increased agronomic NUE and crop yields with EENFs were due to synchrony between N supply and plant demand, thereby enhancing uptake efficiency and reducing N losses via leaching, as well as nitrous oxide emissions (Carson and Ozores-Hampton, 2012; Morgan *et al*., 2009). Sikora *et al*. (2020) reported that the use of SRF could reduce total greenhouse gas (GHGs) emissions by 30% and fertilizer emissions by 50%, thus helping to mitigate global warming and climate change (Jiang *et al*., 2010; Zhang *et al*., 2015).

In addition to agronomic benefits, our results confirm that the use of EENFs (PCU, SCU and UB) could fetch higher economic return compared with CU and FP (Figure 4), mainly as a result of reduced N inputs and labour costs (single time application over split application of CU) and higher cauliflower yields, which corroborates earlier findings (Simonne and Hutchinson, 2005; Van Eerd *et al*., 2017; Wang *et al*., 2020). Per hectare N input costs for EENFs (for PCU, a cost of USA$ 278 and, for SCU, USA$ 285) represented respective increases over the cost CU (USA$ 239) of only 14% and 16% and, for UB (USA$ 234), the difference was even less. These differences were easily covered by the higher cauliflower yields and reduced labour costs of the EENFs, providing farmers with higher net returns over CU. In both the Mid-hills and the Terai, use of PCU, SCU or UB was found to be economically viable and more profitable than use of CU applied in split applications, offering farmers net additional earnings, respectively, of USA$ 2,640, USA$ 2,541 and USA$ 2,745 with the use of PCU, SCU and UB, compared with CU. Moreover, farmers could profit by an additional USA$ 6,145 (PCU), USA$ 6,046 (SCU) or USA$ 6,250 (UB) by changing their traditional nutrient management practices and using EENF products following best management practices.

Research Implications and Way Forward

This study suggests that switching the N source from granular urea to EENFs could help to boost cauliflower productivity and cauliflower farmers' incomes in Nepal, as well as reducing N input by up to 33%, while increasing the average curd yields by 22%. However, our study could not identify the maximum N reduction rate beyond 33% from EENFs; further research is needed on multiple EENFs application rates to determine the maximum reduction rate of N fertilizer in cauliflower for those fertilizers. The higher economic return for EENFs (at least 25% and 50% compared with CU and FP, respectively) could foster economic growth, agricultural development and poverty reduction among vegetable farmers and in farm communities.

In Nepal, formal supplies of urea meet only about 50% of national demand (Panta, 2018). Use of EFNFs could help reduce demand, so that current supplies cover actual need. Hence, there may be a place for policies to foster the availability and use by farmers of EENFs. Particularly, PCU and SCU are not registered in Nepal; policymakers may wish to proceed with registration and promote involvement of public and private actors to obtain and market them. UBs are a registered fertilizer, so policy support for their production in Nepal would foster their widespread availability and affordability for farmers. Given the highest agronomic performance and economic return for UB, the Government of Nepal should allow increased private sector involvement in the production and sale of the UBs, as well as undertaking scaling out and promotional programs, including local training and field demonstrations, in collaboration with relevant stakeholders and farmer organizations.

Conclusion

Use of enhanced efficiency N fertilizers (EENFs) in cauliflower was found agronomically and economically viable compared with the application of CU. EENFs could reduce significant amount of N input due to its higher NUE and maintain higher marketable curd yield compared with the use of CU. Across the districts, farmers use insufficient quantity of fertilizers attributing to larger yield gap; thus, the use of EENFs could be a sustainable approach to close the existing yield gap.

This is the first study that has assessed the agronomic and economic potential of EENFs on cauliflower productivity in Nepal. Thus, further studies are recommended covering diverse agro-ecological zones with varied soil types to come up with comprehensive conclusion to develop scaling out strategies. Moreover, across the globe, there are very few studies that has assessed the potential of EENFs specifically on cauliflower productivity. Therefore, this study could be of high significance for range of stakeholders including academicians, researchers and extension workers at national and international levels.

Supplementary Material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479722000060

CRedit Author Statement. **Naba Raj Pandit:** Conceptualization, methodology, data curation, formal analysis, writing-original draft**.** **Dyutiman Choudhary:** Conceptualization, supervision, writing-review and editing, funding acquisition. **Yam Kanta Gaihre:** Conceptualization, supervision, writing-review and editing. **Shriniwas Guatam:** Conceptualization, supervision, writing-review & editing. **Shashish Maharjan:** Software, formal analysis. **Shree Prasad Vista:** Resources, writing-review and editing.

Acknowledgements. USA Agency for International Development (USAID) is acknowledged for providing support for this research through 'Feed the Future Nepal Seed and Fertilizer Project (Cooperative Agreement number AID-367-IO-16-00001).' EENFs including polymer-coated urea, urea (Thiogro ES) and UB were provided by IFDC through 'Feed the Future Soil Fertility Technology Adoption, Policy Reform and Knowledge Management (Cooperative Agreement Number AID-BFS-IO-15-00001).' We thank cooperatives members/volunteers across the district for their support in selecting farmers' field to conduct the trials. We would like to thank our colleagues (Mr. Surya thapa, Mr Roshan Subedi, Mr. Roshan Shah, Mr. Uttam Kunwar, Mr. Dilli Chalisey, Mr. Resham KC, Mr. Rajendra Upadhyaya, Mr. Kedar Nath Nepal and Mrs. Srijana Poudel) for their practical assistance and regular supervision of the field trials. Finally, we are grateful to Mike Listman for editing to improve the paper's language usage and clarity.

Conflict of Interest. The authors declare no conflict of interest.

References

Agyin-Birikorang S., Winings J.H., Yin X., Singh U. and Sanabria J. (2018). Field evaluation of agronomic effectiveness of multi-nutrient fertilizer briquettes for upland crop production. *Nutrient Cycling in Agroecosystems* **110**, 395–406.

Baral B.R., Pande K.R., Gaihre Y.K., Baral K.R., Sah S.K., Thapa Y.B. and Singh U. (2020). Increasing nitrogen use efficiency in rice through fertilizer application method under rainfed drought conditions in Nepal. *Nutrient Cycling in Agroecosystems* **118**, 1–12.

Belbase P. and Bc L. (2020). Effects of different fertilizers on yield and vitamin C content of cauliflower (Brassica oleracea var. botrytis) – A review. *Asian Journal of Agricultural and Horticultural Research* **6**, 37–46.

Bouyoucos G.J. (1936). Directions for making mechanical analyses of soils by the hydrometer method. *Soil Science* **42**, 225–230.

Brown B.D., Hornbacher A.J. and Naylor D.V. (1988). Sulfur-coated urea as a slow-release nitrogen source for onions. *Journal of the American Society for Horticultural Science* **113**, 864–869.

Carson L.C. and Ozores-Hampton M. (2012). Methods for determining nitrogen release from controlled-release fertilizers used for vegetable production. *Horttechnology* **22**, 20–24.

Carson L.C. and Ozores-Hampton M. (2013). Factors affecting nutrient availability, placement, rate, and application timing of controlled-release fertilizers for Florida vegetable production using seepage irrigation. *Horttechnology* **23**, 553–562.

Chen D., Suter H., Islam A., Edis R., Freney J.R. and Walker C.N. (2008). Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. *Soil Research* **46**, 289–301.

Chen Z., Wang Q., Ma J., Zou P. and Jiang L. (2020). Impact of controlled-release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. *Scientific Reports* **10**, 1–10.

Csizinszky A.A. (1994). Yield response of bell pepper and tomato to controlled-release fertilizers on sand. *Journal of Plant Nutrition* **17**, 1535–1549.

Derrick B.E., Etienne I. and Mathusalem K. (2017). Comparative study of urea in prilled and briquette forms on rice production in Marshlands of Rwanda. *Journal of Fertilizers & Pesticides* **8**, 178.

Devkota K.P., Devkota M., Khadka L., Khadka A., Paudel G., Acharya S. and McDonald A.J. (2018). Nutrient responses of wheat and rapeseed under different crop establishment and fertilization methods in contrasting agro-ecological conditions in Nepal. *Soil and Tillage Research* **181**, 46–62.

Dhakal K., Baral B.R., Pokhrel K.R., Pandit N.R., Thapa S.B., Gaihre Y.K. and Vista S.P. (2020) Deep placement of briquette urea increases agronomic and economic efficiency of maize in sandy loam soil. *AGRIVITA, Journal of Agricultural Science* **42**. https://doi.org/10.17503/agrivita.v42i3.2766

Drost D., Koenig R. and Tindall T. (2002). Nitrogen use efficiency and onion yield increased with a polymer-coated nitrogen source. *HortScience* **37**, 338–342.

Fermont A. and Benson T. (2011). Estimating yield of food crops grown by smallholder farmers. *International Food Policy Research Institute* **1**, 68.

Gaihre Y.K., Singh U., Islam S.M.M., Huda A., Islam M R, Satter M.A., Sanabria J., Islam Md R and Shah A.L. (2015). Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. *Geoderma* **259**, 370–379.

Guertal E.A. (2009). Slow-release nitrogen fertilizers in vegetable production: a review. *Horttechnology* **19**, 16–19.

Jiang J., Hu Z., Sun W. and Huang Y. (2010). Nitrous oxide emissions from Chinese cropland fertilized with a range of slow-release nitrogen compounds. *Agriculture, Ecosystems & Environment* **135**, 216–225.

Jones J.D. (2021). Nutrient use efficiency—A metric to inform 4R nutrient stewardship. *Crops & Soils* **54**, 42–48.

Liu S., Cui S., Zhang X., Wang Y., Mi G. and Gao Q. (2020). Synergistic regulation of nitrogen and sulfur on redox balance of maize leaves and amino acids balance of grains. *Frontiers in Plant Science* **11**, 1777.

McArdle R.N. and McClurg C.A. (1986). Effects of sulfur-coated urea fertilizer regimes on production of processing tomatoes on a sandy loam. *Fertilizer Research* **8**, 259–262.

MoALD. (2019). Statistical information on Nepalese Agriculture 2017/18. Kathmandu, Nepal.

Morgan K.T., Cushman K.E. and Sato S. (2009). Release mechanisms for slow-and controlled-release fertilizers and strategies for their use in vegetable production. *Horttechnology* **19**, 10–12.

Naz M.Y. and Sulaiman S.A. (2016). Slow release coating remedy for nitrogen loss from conventional urea: a review. *Journal of Controlled Release* **225**, 109–120.

Neupane, B., Aryal, K., Chhetri, L.B. and Regmi, S. (2020). Effects of integrated nutrient management in early season cauliflower production and its residual effects on soil properties. *Journal of Agriculture and Natural Resources* **3**, 353–365.

Ojha P. (2016). A study of vegetable and fruit export from Eastern region of Nepal. South Asia Watch on Trade, Economics and Environment (SAWTEE). Kathmandu Var. Printers.

Olsen S.R. and Sommers L.E. (1982). Phosphorus. p. 403–430. AL Page et al.(ed.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA and SSSA, Madison, WI. Phosphorus. p. 403–430. AL Page al.(ed.) Methods soil Anal. Part 2. 2nd ed. Agronomy Mongraphs. 9. ASA SSSA, Madison, WI.

Pandit N.R., Mulder J., Hale S.E., Zimmerman A.R., Pandit B.H. and Cornelissen G. (2018). Multi-year double cropping biochar field trials in Nepal: Finding the optimal biochar dose through agronomic trials and cost-benefit analysis. *Science of the Total Environment*, 637–638. https://doi.org/10.1016/j.scitotenv.2018.05.107

Panta H.K. (2018). Supply chain of subsidized chemical fertilizers in Nepal. *Journal of the Institute of Agriculture and Animal Science* **35**, 9–20.

Perveen S., Ahmad S., Skalicky M., Hussain I., Habibur-Rahman M., Ghaffar A., Shafqat Bashir M., Batool M., Hassan M.M. and Brestic M. (2021). Assessing the potential of polymer coated urea and sulphur fertilization on growth, physiology, yield, oil contents and nitrogen use efficiency of sunflower crop under arid environment. *Agronomy* **11**, 269.

Pooniya V., Shivay Y.S., Pal M. and Bansal R. (2018). Relative performance of boron, sulphur and zinc coatings onto prilled urea for increasing productivity and nitrogen use efficiency in maize. *Experimental Agriculture* **54**, 577–591.

Ransom C.J. (2014). *Nitrogen use efficiency of polymer-coated urea*. MS thesis. Brigham Young University.

Ray M. and Mishra N. (2017). Effect of weather parameters on the growth and yield of Cauliflower. *Environment Conservation Journal* **18**, 9–19.

Rodríguez V.M., Soengas P., Alonso-Villaverde V., Sotelo T., Cartea M.E. and Velasco P. (2015). Effect of temperature stress on the early vegetative development of Brassica oleracea L. *BMC Plant Biology* **15**, 1–9.

Rossini F., Provenzano M.E., Sestili F. and Ruggeri R. (2018). Synergistic effect of sulfur and nitrogen in the organic and mineral fertilization of durum wheat: grain yield and quality traits in the Mediterranean environment. *Agronomy* **8**, 189.

Shrestha R.B., Huang W.-C., Gautam S. and Johnson T.G. (2016). Efficiency of small scale vegetable farms: policy implications for the rural poverty reduction in Nepal. *Agricultural Economics* **62**, 181–195.

Shrestha R.K. and Maskey, S.L. (2005). Associative nitrogen fixation in lowland rice. *Nepal Agriculture Research Journal* **6**, 112–121.

Sikora J., Niemiec M., Szeląg-Sikora A., Gródek-Szostak Z., Kuboń M. and Komorowska M. (2020). The impact of a controlled-release fertilizer on greenhouse gas emissions and the efficiency of the production of Chinese cabbage. *Energies* **13**, 2063.

Simonne E.H. and Hutchinson C.M. (2005). Controlled-release fertilizers for vegetable production in the era of best management practices: teaching new tricks to an old dog. *Horttechnology* **15**, 36–46.

Snyder C.S. (2017). Enhanced nitrogen fertiliser technologies support the '4R'concept to optimise crop production and minimise environmental losses. *Soil Research* **55**, 463–472.

Team R.C. (2019). R: A Language and Environment for Statistical Computing.

Trenkel M.E. (1997). *Controlled-release and stabilized fertilizers in agriculture*. Paris: International Fertilizer Industry Association.

Trenkel M.E. (2010). *Slow-and controlled-release and stabilized fertilizers: an option for enhancing nutrient use efficiency in agriculture*. Paris: IFA, International Fertilizer Industry Association.

Van Eerd L.L., Turnbull J.J.D., Bakker C.J., Vyn R.J., McKeown A.W. and Westerveld S.M. (2017). Comparing soluble to controlled-release nitrogen fertilizers: storage cabbage yield, profit margins, and N use efficiency. *Canadian Journal of Plant Science* **98**, 815–829.

Vanlauwe B., Bationo A., Chianu J., Giller K.E., Merckx R., Mokwunye U., Ohiokpehai O., Pypers P., Tabo R. and Shepherd K.D. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* **39**, 17–24.

Walkley A. and Black I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38.

Wang C., Lv J., Coulter J.A., Xie J., Yu J., Li J., Zhang J., Tang C., Niu T. and Gan Y. (2020). Slow-release fertilizer improves the growth, quality, and nutrient utilization of wintering Chinese Chives (Allium tuberosum Rottler ex Spreng.). *Agronomy* **10**, 381.

Zhang X., Davidson E.A., Mauzerall D.L., Searchinger T.D., Dumas P. and Shen Y. (2015). Managing nitrogen for sustainable development. *Nature* **528**, 51–59.

Cite this article: Pandit NR, Gaihre YK, Gautam S, Maharjan S, Vista SP, and Choudhary D. Enhanced-efficiency nitrogen fertilizer boosts cauliflower productivity and farmers' income: Multi-location and multi-year field trials across Nepal. *Experimental Agriculture*. https://doi.org/10.1017/S0014479722000060