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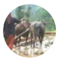

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ORIGINAL ARTICLE

Increasing nitrogen use efficiency in rice through fertilizer application method under rainfed drought conditions in Nepal

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Abstract Nitrogen (N) is the most important yield-limiting plant nutrient. Despite various measures available for improvement of N management, nitrogen use efficiency (NUE) is still very low in rice (*Oryza sativa* L.), particularly under rainfed conditions. A field experiment was conducted at the Regional Agricultural Research Station, Banke, Nepal, during the rainy seasons of 2017 and 2018 to study the effects of nitrogen application method on NUE and grain yields across different varieties. The field experiment was laid out in a split-plot design, consisting of three rice varieties—*Arize 6444, Radha-4*, and *Sukkha Dhan-3*—as the main plots and five fertilizer treatments in sub-plots, and replicated thrice. The five fertilizer treatments included control (0 kg N ha^{-1}), broadcast prilled urea at 78 kg N ha^{-1} and 100 kg N ha^{-1}, and deep placement of prilled urea and briquetted urea at 78 kg N ha^{-1}. Both rice variety and fertilizer treatment had a significant ($p < 0.05$) effect on grain yield. The hybrid variety (*Arize 6444*) increased grain yield by 23% compared to *Sukkha Dhan-3* (4.9 Mg ha^{-1}). Deep-placed briquetted urea increased grain yield by 21–23% (6.7 Mg ha^{-1}) compared to broadcast and deep-placed prilled urea. A higher grain yield for briquetted urea positively correlated ($r = 0.43$) with the number of tillers per hill. Deep-placed briquetted urea increased NUE (apparent N recovery, agronomic NUE, partial factor productivity of N, and physiological efficiency by 44%, 40%, 34%, and 3%, respectively), while reducing ammonia volatilization by 57% compared to the current recommended rate of broadcast prilled urea. Our results confirm that deep placement of briquetted urea significantly increases grain yields and NUE of rainfed rice.

Keywords Briquetted urea · Nepal · Nitrogen use efficiency · Urea deep placement · Rainfed rice

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Introduction

Rice is the staple food for more than half of the world's population (FAO 2013). Globally, it is cultivated on 163 million hectares (ha), and an estimated 90% of all rice is produced and consumed in Asia (FAO 2013). In Nepal, rice is cultivated on 1.43 million ha, producing 4.8 million tons (MoAD 2014/15), and contributes 20% to the agricultural gross domestic product (Ghimire et al. 2013). Despite that fact, average rice productivity is much lower (3.2 Mg ha^{-1}) compared to other South Asian countries, including India (3.60 Mg ha^{-1}), Pakistan (3.72 Mg ha^{-1}), Bangladesh (4.55 Mg ha^{-1}), Bhutan (4.01 Mg ha^{-1}), and Sri Lanka (3.76 Mg ha^{-1}) (FAO 2015). Lower productivity may be associated with a decline in soil fertility, insufficient and imbalanced use of fertilizers, intensive cropping systems, use of traditional varieties, and poor farmer awareness of improved crop management practices (Baral et al. 2019).

An urgent need in rice farming is to increase yields while maintaining low nitrogen (N) inputs to maximize nitrogen use efficiency (NUE). The NUE (defined as the fraction of applied N uptake by plant) in lowland rice rarely exceeds 30% (Ladha et al. 2005). This may be much lower under rainfed conditions (Balasubramanian et al. 2004) due to blanket application of fertilizers without consideration of variations in the indigenous soil N supply capacities, crop N uptake efficiency, soil moisture conditions (Inman et al. 2005), and agro-climatic and management conditions (Dobermann et al. 2003). A single broadcast application of prilled urea (PU) as a basal fertilization often supplies an excess amount of N to plants at the early growth stage, when demand for N is lower. Therefore, a large portion of N may be lost from soil–plant systems via ammonia (NH_3) volatilization, surface runoff, and leaching (Savant and Stangel 1990; Mohanty et al. 1998). Since mineralized N cannot be retained in soil for a long period of time, plants show the N deficiency at the latter growth stages, resulting in lower NUE, grain yields, and economic returns. NUE could be improved by applying N at multiple splits, which reduces N loss by synchronizing the N supply and plant demand (Kaushal et al. 2010; Kamruzzaman et al. 2013; Jeong et al. 2014). However, this is challenging under rainfed conditions because farmers must synchronize fertilizer application with rainfall (to dissolve the fertilizer) rather than plant N demand. For this reason, farmers cannot apply the follow-on splits during an extended dry period or flooding conditions.

Of several proposed strategies to increase NUE and reduce N loss, urea deep placement (UDP) is considered an effective method for lowland rice (Savant and Stangel 1990; Kapoor et al. 2008; Bandaogo et al. 2015; Miah et al. 2016). Deep-placed N fertilizer remains in oxygen-deprived zones longer, and its movement to the soil surface and subsequent movement with floodwater is negligible (Kapoor et al. 2008). Therefore, UDP is an effective method to reduce N loss, particularly from NH_3 volatilization, surface runoff (Sommer et al. 2004; Rochette et al. 2013), nitrification, and subsequent denitrification (Chien et al. 2009), hence reducing nitrous oxide emissions (Gaihre et al. 2015). In rainfed conditions, however, soils receive moisture only during rainfall, which is unpredictable under current climatic scenarios. One-time application of N fertilizer (when the water regime is suitable), such as urea deep placement (UDP), may increase NUE in rainfed conditions where volatilization is the major source of N loss (Mohanty et al. 1998). UDP has performed better in aerobic rice (Xiang et al. 2013) and upland crops, such as potato (Azam et al. 2012) and cabbage (Hussain et al. 2010). However, using UDP to improve NUE has not been assessed sufficiently under rainfed rice cultivation. Therefore, we hypothesize that UDP will perform better under rainfed rice conditions.

In general, there is a positive linear relationship between N uptake and grain yield. However, some crop varieties (genotypes) produce different grain yields with the same amount of N uptake due to the difference in internal N use efficiency (IE_N, defined as the amount of grain yield produced relative to N uptake) (Tirol-Padre et al. 1996; Singh et al. 1998). A difference in IE_N may arise from differences in internal N requirements for growth and the plant's ability to translocate, distribute, and mobilize absorbed N to and from various organs (Ladha et al. 1998; Zhang et al. 2007). Therefore, poor selection of variety (e.g., drought tolerant, fertilizer responsive, etc.) and inefficient fertilizer management are the major challenges to boosting the productivity of rainfed rice.

This field study was conducted under rainfed conditions, aiming to understand the NUE of different rice varieties with various forms of N fertilizers and application methods. The objectives were to:

- Identify a suitable N fertilizer application method to increase grain yield and NUE of rainfed rice.
- Evaluate the interaction between N management and crop variety on grain yield and NUE.

Materials and methods

Study site and weather conditions

A field experiment was conducted at the Regional Agricultural Research Station, Khajura, Banke, Nepal (28°11′30″ N and 81°58′89″ E) during the rainy seasons (monsoon seasons) of 2017 and 2018. The experimental site is one of the dry rainfed areas of Nepal that has a subtropical climate with a wet summer and dry winter. Average (30-year average) annual rainfall ranges from 1000 to 1500 mm, and more than 80% of annual rainfall occurs in the monsoon season (June–September). Total rainfall during the experimental period (June-October) was similar for both years, i.e., 980 mm (Fig. S1). Rice is cultivated during the monsoon season, followed by wheat. However, in recent years, the drought period has extended due to an uneven distribution pattern; monsoon rain often starts late and ends early.

Experimental setup and crop management

A field experiment was conducted in silty clay loam soil (26% sand, 38% silt, and 36% clay). The details of other soil physicochemical properties are given in Table 1. Experimental treatments were laid out in a split-plot design with three replications; rice varieties were in the main plots and fertilizer treatments were in the sub-plots. The varieties included *Arize 6444* (a popular hybrid variety of western Terai), *Radha-4* (an early-maturing, widely adopted variety), and *Sukkha Dhan-3* (a drought-tolerant variety recommended for rainfed drought conditions). The five fertilizer treatments were control (N0, 0 kg N ha^{-1}), broadcast application of prilled urea applied at 78 kg N ha^{-1} (PU-N78) and 100 kg N ha^{-1} (PU-N100), and deep placement of prilled urea at 78 kg N ha^{-1} (PUDP-N78) and briquetted urea at 78 kg N ha^{-1} (UBDP-N78). Broadcast application of PU at 100 kg N ha^{-1} is the government's standard recommendation.

Table 1 Soil physical and chemical properties of the experimental site prior to start of the experiment (Regional Agriculture Research Station, Banke, Nepal)

Parameters	Unit	Value
Organic matter (OM)	%	2.33
Total N	%	0.127
Available P_2O_5	kg ha^{-1}	41.1
Exchangeable K_2O	kg ha^{-1}	65
Soil pH (1:2)		6.7
Bulk density	Mg m^{-3}	1.44
Soil texture		
Sand	%	26
Silt	%	38
Clay	%	36
B (water soluble)	μg g^{-1}	1.13
S (water soluble)	%	< 0.1
Exchangeable Mg	mEq 100 g^{-1}	4.38
Cu	μg g^{-1}	0.1
Zn	μg g^{-1}	1.82
Mn	μg g^{-1}	8.27
Fe	μg g^{-1}	21.33
Mo	μg g^{-1}	0.2

Phosphorus (P) and potassium (K) were applied during the final land preparation at a rate of 30:30 kg ha^{-1} P_2O_5:K_2O via single superphosphate and muriate of potash, respectively. The experimental plots (14.4 m^2, 3.6 m × 4.0 m) were prepared for seedling transplanting by digging with a spade 15 days prior to transplanting. Light irrigation was applied during puddling time. Two to three rice seedlings (25 days old) were transplanted at a distance of 0.2 m × 0.2 m (row to row and hill to hill). PU was broadcasted in three equal splits—1 week after transplanting, 25–30 days after transplanting (DAT), and before panicle initiation stage. A urea briquette (UB), weighing 2.7 g, was deep placed into the center of four rice hills (0.4 m × 0.4 m) 1 week after seedling transplanting. The UB was inserted 70–100 mm below the soil surface by making a small hole using a stick and then covered properly with soil. PU was deep placed uniformly in a furrow made by a hoe in an alternate row (0.4 m) and covered with soil.

Other cultural operations, such as weeding and plant protection measures, were the same for all treatments. Since the experiment was conducted under rainfed conditions, supplemental irrigation was applied only during puddling and transplanting time.

Measurement and data collection

Plant height and tiller numbers

Ten hills were selected randomly from each plot and tagged to record periodic plant height and number of tillers. Plant heights and total dry matter accumulation were measured at 30, 45, and 60 DAT and at harvest. To determine the total dry matter production, two hills from each plot were destructively harvested, leaving the border rows. Plant samples were dried in an oven at 65–70 °C for 48 h.

Yield, yield components, and harvest index

The average number of tillers and panicles was recorded from ten randomly selected plants. The ten selected panicles were used to measure panicle length and number of grains per panicle. For grain and straw yields, crop was harvested from a 10-m^2 area. The grains were separated by threshing (after 3 days of sun drying) using a mini paddy thresher. Grain yield was calculated at 14% moisture content after air drying and cleaning. A test weight was recorded from 1000 grains. Total straw yield was recorded correcting moisture based on oven-dried samples. The harvest index was calculated dividing grain yields (economic yields) by total biological yields.

Nitrogen use efficiency

Nitrogen contents of grain and straw samples were analyzed with the standard method (Bremner and Mulvaney 1982) to calculate the N uptake and NUE. Different forms of NUE, including agronomic efficiency, recovery efficiency, and partial factor productivity, were calculated using the following formulas (Ladha et al. 2005).

- Recovery efficiency of N (RE_N) = (UN_N—UN0)/(FN—FN0), kg N uptake per kg N applied
- Agronomic efficiency of N (AE_N) = (GY_N—GY_0)/(FN—FN0), kg grain yield increase per kg N applied
- Partial factor productivity of N (PFP_N) = GY_N/FN, kg grain yield per kg N applied
- Physiological efficiency of applied N (PE_N)-= (GY_N—GY_0)/(UN_N—UN_0), kg grain yield increase per kg N uptake
- Internal efficiency of N (IE_N) = GY_N/UN_N, kg grain per kg N uptake
- Utilization efficiency (UE_N) = Physiological efficiency x Apparent N recovery, kg kg^{-1}

where GY_N = total grain yield when N applied, FN = total N fertilizer applied, GY_0 = total grain yield without N application, UN_N = total N uptake in N application treatment, UN_0 = total N uptake without N application treatment.

Soil samples were collected before transplanting and after harvesting from each plot and analyzed for soil organic carbon (C), pH, total N, available P_2O_5, and exchangeable K_2O. Periodic soil samples were taken after each N fertilizer application to monitor the N dynamics and soil pH.

Measurement of ammonia volatilization

Ammonia (NH_3) emissions were estimated in the collected air samples from a closed chamber by the sulfuric acid (H_2SO_4) trapping method, as used by Ndegwa et al. (2009). A plastic bucket (0.15-m diameter and 0.30-m depth) was inserted 0.05 m into the soil in each plot and left for 30 min to collect gas samples. Measurements were taken over 18 h of urea application (until NH_3 was detected in the trap). An air sample was collected using a 30-mL syringe with a stainless-steel needle and immediately injected into a beaker containing 50 mL of sulfuric acid (0.05 mol L^{-1}) and shaken well to dissolve it. The beaker was closed with paraffin to avoid trapping other gases. The excess H_2SO_4 (that which did not react with NH_3) was calculated by titrating with the standard NaOH solution (0.1 mol L^{-1}) to determine the exact amount of H_2SO_4 consumed by NH_3. The amount of NH_3 was calculated using the following formula:

$$\mathrm{V_{React}H_2SO_4 = V_{total}H_2SO_4 - V_{excess}H_2SO_4(mL),}$$
$$\mathrm{V_{excess}H_2SO_4 = V\ NaOH}$$
$$\mathrm{1\ mL\ of\ 0.05\ mol/}$$
$$\mathrm{L\ H_2SO_4 corresponds\ to\ 1.7\ mg\ of\ NH_3.}$$

Data analysis

An analysis of variance (ANOVA) was carried out using Genstat 13.2 (VSN International Ltd, Hemel Hempstead, United Kingdom) to test for significant differences between treatment means. Normality and of homogeneity of residual distribution was tested using Q–Q plots and Levene's test, respectively. A pair-wise mean comparison of the treatment means was done with least significance difference (LSD) test at a 5% significance level.

Results

Rice growth and yields

Fertilizer treatment significantly affected plant heights (Table 2). The highest plant height was observed in treatment with UBDP. Similarly, UBDP-N78 had a significantly higher plant growth rate up to 45 DAT compared to other treatments, and this higher growth rate resulted in significantly higher dry matter accumulation at harvest. Variety had a significant effect on growth rate and dry matter accumulation only at 45 DAT. The highest dry matter accumulation was observed in *Radha-4*, which was on par with *Arize 6444*, while the lowest was observed in *Sukkha Dhan-3*. Overall, growth rates were higher during 45–60 DAT compared to other growth stages (Table 2).

UBDP-N78 had a significantly ($p < 0.05$) higher number of effective tillers per hill and number of grains per panicle. Number of tillers was not affected either by variety or interaction of variety and fertilizer (Table 3). UBDP-N78 produced the highest number of tillers per hill, which was similar to PU-N100. The number of grains per panicle was significantly affected by rice variety and fertilizer treatment (Table 3). There was no interaction effect of variety and fertilizer treatment. The hybrid variety produced a significantly higher number of grains per panicle compared to the other two varieties. Fertilizer and variety had an interaction effect on the test weight. The control treatment had a significantly lower test weight for the hybrid variety compared with the other two varieties, while the *Radha-4* variety with PUDP-N78 produced the highest test weight (Fig. 1).

Both variety and fertilizer treatment independently affected grain yield (Figs. 2, 3). Among fertilizer treatments, UBDP-N78 produced the highest yield, which was significantly higher than PU-N78 and PUDP-N78. At 78 kg N ha^{-1}, deep-placed urea briquette increased grain yield by 21% over broadcast application of PU. Compared to the current government-recommended rate (100 kg N ha^{-1}), the deep-placed urea briquette with 22% less N produced similar grain yields (Fig. 3). The hybrid variety produced the highest grain yield (6.0 Mg ha^{-1}), followed by *Radha-4* (5.7 Mg ha^{-1}) (Fig. 2). Straw yield was affected only by fertilizer treatment. The highest straw yield was recorded in UBDP-N78, which was similar to PU-N100 (Fig. 3).

Nitrogen uptake and use efficiency

Fertilizer treatment affected total N uptake and different components of NUE, but interaction of fertilizer and variety was not significant (Table 4). UBDP-N78 increased N uptake by 6% and 18% compared to broadcast application of PU at N78 and N100 (the current recommended rate), respectively. With the increase in N uptake, deep-placed UB at 78 kg N ha^{-1} increased $\mathrm{RE_N}$ by 44% (69.75% vs. 48.35%), $\mathrm{AE_N}$ by 40% (41.98 vs. 29.8 kg grain kg^{-1} N), $\mathrm{PFP_N}$ by 34%, and $\mathrm{UE_N}$ by 50% compared to broadcast application of PU at the current recommended rate (PU-N100) (Table 4), while at the same time reducing N input by 22%. Contrary to UBDP-N78, PUDP-N78 had no additional advantage over PU-N78. Variety had a significant effect only on $\mathrm{PFP_N}$, in which *Sukkha Dhan-3* was lower (64 kg grain kg^{-1} N) compared to hybrid (80 kg grain kg^{-1} N) and *Radha-4* (75 kg grain kg^{-1} N).

NH_3 emissions

Fertilizer treatment significantly affected NH_3 emissions, but variety had no effect on emissions. Deep placement of both UB and PU at 78 kg N ha^{-1} significantly reduced cumulative NH_3 emissions by

Table 2 Plant growth rate and total dry matter accumulation across different growth stages of rice under different varieties and fertilizer treatments

Treatment	Plant height (m)	Plant growth rate (g m^{-2} day^{-1})				Total dry matter (g hill^{-1})			
		TP-30DAT	30–45 DAT	45–60 DAT	60 DAT-Maturity	30 DAT	45 DAT	60 DAT	At maturity
Variety									
Arize 6444	0.90	6.94	31.43a	28.7	18.41	8.33	26.7a	43.9	64.75
Radha-4	0.88	7.6	31.0a	30.7	16.66	9.12	27.72a	46.1	64.44
Sukkha Dhan-3	0.88	6.07	25.57b	30.2	18.72	7.29	22.45b	40.6	61.46
Fertilizer									
N0	0.81d	4.92d	19.17c	23.1	11.45	5.90d	17.40d	31.2c	43.56c
PU-N78	0.86c	6.03cd	26.76b	30.5	17.59	7.23cd	23.00c	41.3b	59.52b
PUDP-N78	0.89b	7.49b	28.09b	33.1	19.91	8.99b	25.84bc	45.7b	68.21b
UBDP-N78	0.98a	8.94a	39.79a	32.7	22.09	10.73a	33.79a	53.4a	78.85a
PU-N100	0.89bc	6.99bc	32.86b	30.0	18.63	8.38bc	28.10b	46.1b	67.60b
ANOVA p value									
Years	0.07	0.003	0.08	0.04	0.172	0.003	0.054	0.345	0.425
Variety	0.601	0.07	0.01	0.947	0.797	0.07	< 0.01	0.334	0.575
Fertilizer	< 0.01	< 0.01	< 0.01	0.235	0.06	< 0.001	< 0.001	< 0.01	< 0.01
Y × V	0.503	0.664	0.03	0.345	0.735	0.664	0.017	0.518	0.502
Y × F	0.391	0.789	0.03	0.963	0.385	0.789	0.03	0.393	0.943
V × F	0.968	0.652	0.354	0.61	0.827	0.652	0.287	0.856	0.973
Y × V × F	0.18	0.061	0.570	0.562	0.656	0.061	0.113	0.646	0.527

Values are means of 2 years

Means followed by same letters in a column within variety and fertilizer are not significantly at 5% level. N0 = control-without N fertilizer, PU-N78 = prilled urea 78 kg N ha^{-1}, UBDP-N78 = urea briquette deep placement 78 kg N ha^{-1}, PU-N100 = prilled urea 100 kg N ha^{-1}

40–57% compared to broadcast PU treatments (Fig. S2). Emissions from deep-placed treatments were similar to the control treatment. However, this measurement includes cumulative emissions occurring over 18 h of fertilizer application.

Discussion

Effects of nitrogen placement method and variety on rice growth and yield

Deep placement of UB significantly ($p < 0.05$) increased grain yield (Fig. 3). These results are in close agreement with previous studies conducted under an irrigated rice system (Savant and Stangel 1990; Alam et al. 2013; Bandaogo et al. 2015; Huda et al. 2016). The higher grain yield in the UBDP treatment was due to the increase in the effective number of tillers per hill and number of grains per panicle (Table 3). Similar to our results, Wu et al. (2017) also observed an increased number of panicles with deep placement of N fertilizer. In our study, UBDP increased the crop growth rate (transplanting to 45 DAT) and accumulation of dry matter across different growth stages (Table 2), which resulted in higher grain yields. The increased crop growth rate, yield components, and yields with the deep-placed UB treatment is probably due to a continuous supply of N as per the plant's demand. In comparison to broadcast N fertilizer, deep placement of N fertilizer ensures a continuous supply of N throughout the crop growth period by retaining a higher amount of N at 50–150 mm depth (Siddique et al. 2019), which

Table 3 Number of effective tillers (panicles) per hill and grains per panicle across different varieties and fertilizer treatments

Treatment	No. of effective tillers/hill	No. of grains/panicle
Variety		
Arize 6444	10.01a	168.4a
Radha-4	10.40a	138.1b
Sukkha Dhan-3	9.81a	138.9b
Fertilizer		
N0	8.86b	128.3c
PU-N78	9.62b	140.7bc
PUDP-N78	9.58b	145.2b
UBDP-N78	11.57a	165.3a
PU-N100	10.74a	162.8a
ANOVA *p* values		
Years	0.072	0.06
Variety	0.76	0.003
Fertilizer	< 0.01	< 0.001
Y × V	0.789	0.332
Y × F	0.109	0.418
V × F	0.715	0.579
Y × V × F	0.717	0.501

Values are means of 2 years

Means followed by same letters in a column within variety and fertilizer are not significantly different at 5% level. N0 = control-without N fertilizer, PU-N78 = prilled urea 78 kg N ha^{-1}, UBDP-N78 = urea briquette deep placement 78 kg N ha^{-1}, PU-N100 = prilled urea 100 kg N ha^{-1}

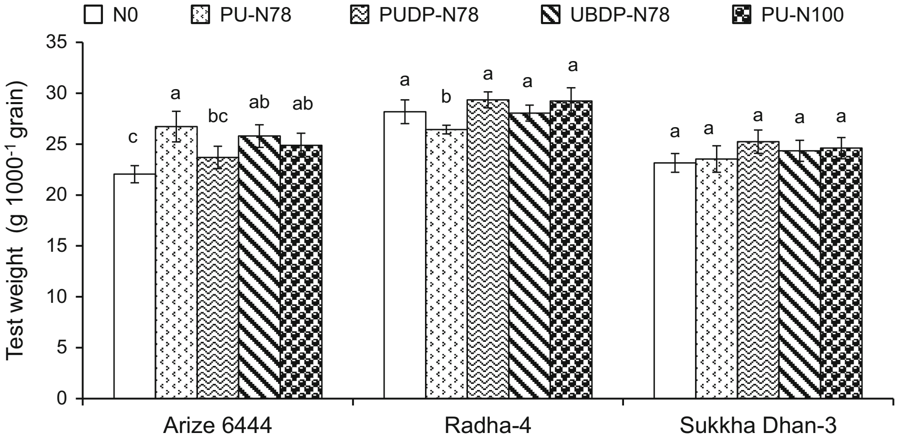

Fig. 1 Thousand-grain weight of rice and interaction effect of varieties and fertilizer treatments. Values are means of 2 years (n = 6). Within a variety, means followed by same letters are not significantly different at 5% level. N0 = control-without N fertilizer, PU-N78 = prilled urea 78 kg N ha^{-1}, UBD-N78 = urea briquette deep placement 78 kg N ha^{-1}, PU-N100 = prilled urea 100 kg N ha^{-1}

increased plant N uptake and thus produced higher yields (Table 4, Fig. 3).

However, in this study, deep placement of PU was not effective compared to deep-placed briquetted urea. Deep placement of PU is as effective as with UB under irrigated conditions (Yao et al. 2017; Wu et al. 2017) in which the moisture regime can be controlled. However, our results suggest that deep placement of PU may not be an effective approach under drought-prone rainfed conditions. The lower performance could be associated with several factors, including improper coverage of urea by soil because of difficulty opening and closing the furrow due to dry soil. Compared to deep-placed UB (point placement), more

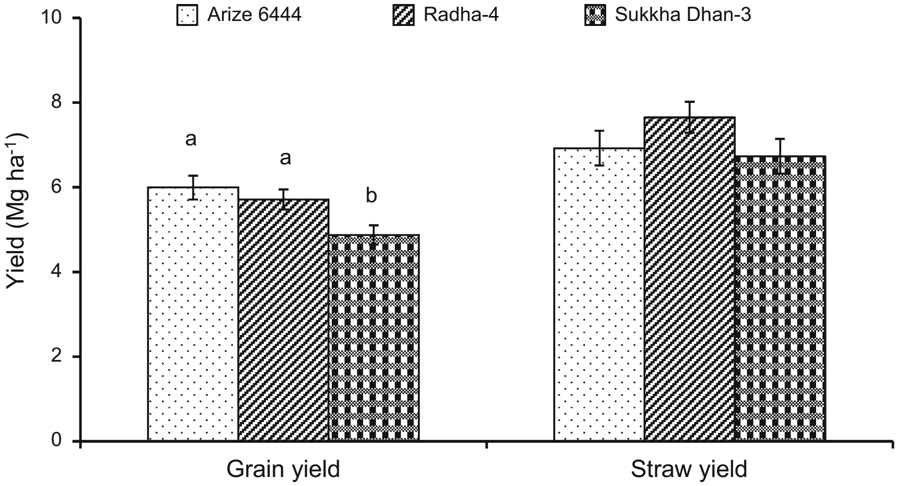

Fig. 2 Effects of rice varieties on rice grain yield and straw yield (straw yields were not significantly different). Values are means across fertilizer treatments and years (n = 30). Within response variable, means followed by same letters are not significantly different at 5% level

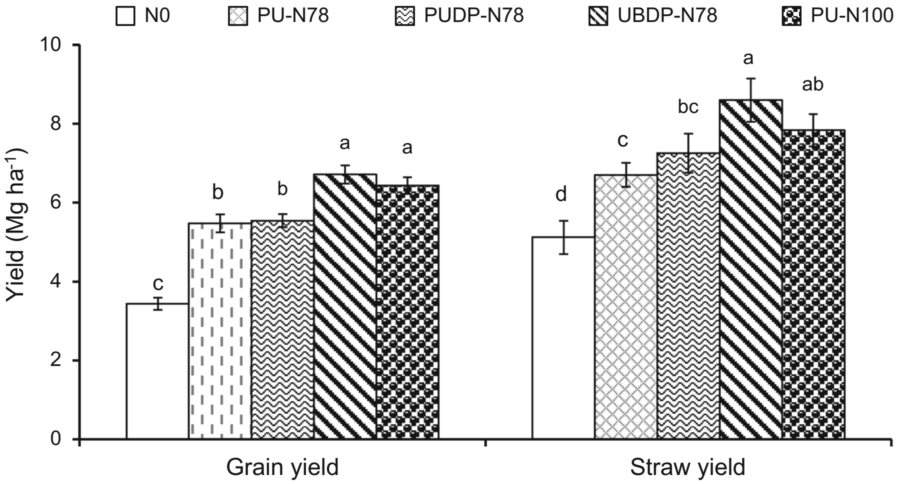

Fig. 3 Effects of fertilizer treatments on rice grain yield and straw yield. Values are means across varieties and years (n = 18). Within response variable, means followed by same letters are not significantly different by LSD at 5% level. N0 = control-without N fertilizer, PU-N78 = prilled urea 78 kg N ha^{-1}, UBDP-N78 = urea briquette deep placement 78 kg N ha^{-1}, PU-N100 = prilled urea 100 kg N ha^{-1}

surface area could have been in contact with soil in deep-placed PU, since it was applied uniformly in a furrow. If not covered properly, this may provide more chance of N leakage to surface soils through NH_3 volatilization. In addition, urea exposure to oxygen may increase nitrification and subsequent denitrification with rainfall. Therefore, it did not increase NUE and grain yields compared to deep-placed UB.

The effect of deep-placed UB on grain yield was consistent across varieties and years, suggesting that deep placement is effective for both improved and hybrid varieties. In our study, the highest grain yield (6.0 Mg ha^{-1}) was recorded in hybrid (*Arize 6444*), followed by *Radha-4* (5.7 Mg ha^{-1}) and *Sukkha Dhan-3* (drought-tolerant variety). The yield difference among varieties is probably due to the difference in genetic potential. Hybrid produced a higher number of grains per panicle compared to the other two rice varieties. Interestingly, plant growth was not different across rice varieties until 30 DAT but was significantly different during 30–45 DAT. *Sukkha Dhan-3* had a slower growth rate compared to hybrid (*Arize 6444*) and *Radha-4*, which resulted in less accumulation of photosynthates (dry matter accumulation). The positive relationship between the number of grains per panicle and the N supply shows that N is the most important determining factor, besides genotypic

Table 4 Total N uptake and different components of NUE of rice across varieties and fertilizer treatments

Treatment	N uptake (kg ha^{-1})	AE_N (kg grain kg^{-1} N)	PFP_N (kg grain kg^{-1} N)	RE_N (%)	PE_N (%)	IE_N (%)	UE_N (%)
Variety							
Arize 6444	97.6	36.05	79.53a	50.80	175.9	55.96	67.79
Radha-4	99.7	29.61	74.79a	54.50	132.6	52.74	63.40
Sukkha Dhan-3	97.0	27.8	64.35b	55.95	107.6	51.57	51.94
Fertilizer							
N0	62.5d						
PU-N78	101.6bc	26.01b	70.17b	50.21b	110.3	44.20c	46.19b
PUDP-N78	98.9c	26.92b	71.09b	46.69b	144.0	55.07b	54.14b
UBDP-N78	116.9a	41.88a	86.02a	69.75a	152.49	53.84b	86.41a
PU-N100	110.8ab	29.83b	64.28c	48.35b	148.09	60.59a	57.43b
ANOVA *p* value							
Years	0.333	0.338	0.32	0.381	0.434	0.438	0.940
Variety	0.945	0.151	0.011	0.766	0.300	0.510	0.215
Fertilizer	< 0.001	< 0.01	< 0.01	0.029	0.393	< 0.001	< 0.001
Y × V	0.573	0.938	0.903	0.72	0.445	0.057	0.312
Y × F	0.815	0.249	0.224	0.822	0.222	< 0.001	0.431
V × F	0.945	0.296	0.294	0.96	0.817	0.112	0.764
Y × V × F	0.935	0.155	0.153	0.931	0.227	0.519	0.900

Values are means of 2 years

Means followed by same letters in a column within variety and fertilizer are not significantly different at 5% level. N0 = control-without N fertilizer, PU-N78 = prilled urea 78 kg N ha^{-1}, UBDP-N78 = urea briquette deep placement 78 kg N ha^{-1}, PU-N100 = prilled urea 100 kg N ha^{-1}

characteristics, for increasing the number of grains per panicle.

Effects nitrogen placement on nitrogen use efficiency

Recovery efficiency of N (RE_N, kg N uptake kg^{-1} N applied) can be increased by synchronizing N supply with plant demand, which improves plant uptake and reduces N loss from soils. Previous studies reported that urea deep placement in lowland rice fields under favorable conditions (irrigated) is effective in increasing RE_N by increasing plant N uptake and reducing N loss (Rochette et al. 2013; Huda et al. 2016). In our study, the deep-placed urea briquette increased various forms of NUE, such as RE_N, AE_N, and PFP_N. The RE_N increased with deep placement due to higher N uptake (Table 4) and lower N loss, particularly from NH_3 volatilization (Rochette et al. 2013; Huda et al. 2016). The deep-placed treatments increased N uptake by up to 18% and reduced NH_3 emissions by up to 57%. Huda et al. (2016) reported that UDP significantly reduced the amount of NH_4^+–N in floodwater and NH_3 volatilization, confirming that UDP retains N in ammonium form for a longer period of time in an anaerobic zone of the soil and makes it available for plant uptake. It is important to note that NH_3 emission was measured for only 18 h in this study because the magnitude of emissions was similar to the control treatment after 18 h. However, some emissions could continue throughout the rice-growing season. There could be underestimation of the emissions, as the measurement did not cover the entire rice-growing season. More measurements are needed to quantify the absolute amount of loss through volatilization. Lower RE_N and AE_N in broadcast urea is most likely related to loss of N via volatilization prior to plant uptake due to a supply in excess of the plant's demand (Huda et al. 2016; Liang et al. 2013). Excess supply was observed when N was applied as a blanket application, as in the current recommended practice.

Most previous studies with UDP were conducted under favorable conditions (irrigated), in which irrigation water could be controlled as required (Rochette et al. 2013; Yao et al. 2017). Our results confirm that deep placement of UB is equally effective under rainfed conditions as under irrigated conditions. However, more on-farm experiments under a variety of management conditions across different agro-ecologies considering economic returns should be conducted for wider recommendation.

Effects of variety on nitrogen use efficiency

Crop genetic improvements could increase rice yields and NUE (Tang et al. 2019; Yu et al. 2019). In general, grain yields increase with increased N uptake, but some genotypes produce different grain yields with the same amount of N uptake due to differences in the IE_N of plants (Singh et al. 1998; Tirol-Padre et al. 1996). The genetic growth differences arise from differences in the absorption and assimilation efficiency of NH_4^+ and other N species and their regulation—ability to translocate, distribute, and mobilize absorbed N to and from various organs—as well as root morphology and root-induced changes in the rhizosphere affecting N mineralization (Ladha et al. 1998; Shrestha and Ladha 1996). However, in our study, the effect of variety on different forms of NUE was not significant, except the hybrid variety increased PFP_N, suggesting that the hybrid variety utilized more indigenous N. As fertilizer treatment and variety had no significant effect on either grain yield or RE_N, deep placement of UB could be effective to increase yield and NUE across different varieties, including hybrids.

Conclusion

N fertilizer management under rainfed conditions is challenging, since farmers may not be able to properly time the application of N topdressing due to extended drought or flood (excess rainfall) because of unpredictable rainfall. We tested various forms of N fertilizer sources and modes of application in rice, ranging from broadcasting to deep placement of N, to improve NUE and crop productivity. This study suggests that deep placement of urea briquettes is a solution to increase grain yields and NUE of a range of improved varieties, including hybrid, under rainfed conditions. Deep placement of urea briquettes saves a significant amount of N fertilizer and time spent on follow-on split applications, which helps reduce environmental loss of N and improve the net economic return to farmers. It also has positive implications for government subsidy programs, in which the government provides a subsidy for fertilizers, particularly in the developing countries, such as Nepal. However, more on-farm field studies should be conducted across different management conditions and agro-ecologies for its wider recommendation.

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