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Fertilizer Deep Placement Increases Rice Production: Evidence from Farmers' Fields in Southern Bangladesh

Md. Abdul Mazid Miah, Yam Kanta Gaihre, Grahame Hunter, Upendra Singh,* and Syed Afzal Hossain

ABSTRACT

Efficient use of fertilizer is needed to meet the increasing food demand, minimize negative environmental impacts, and maximize farmers' profits. Fertilizer deep placement (FDP) could be one of the best management techniques to achieve these multiple benefits. Experiments were conducted in 115 farmers' fields spread over 35 upazilas across eight districts over nine contiguous rice (*Oryza sativa* L.) growing seasons during 2009 to 2012 in southern Bangladesh to compare the effects of deep placement of urea briquettes (UB) and nitrogen–phosphorus–potassium briquettes (NPK), with farmers' broadcast prilled urea (PU) on rice yield and net economic return. Deep placement of either UB or NPK significantly increased grain yields and net economic return across all the rice-growing seasons and years compared to PU. Across the years, average yield increase in UB and NPK over PU was higher during the Aus and Aman (wet) seasons (21–31%) than in the Boro (dry) season (11–17%). In addition to increase in grain yield, deep placement of UB and NPK saved urea by 33 and 44%, respectively, during the Aus–Aman seasons, and by 35 and 28% during the Boro season. The deep placement of one 2.4 g NPK (~44 kg N ha^{-1}) for the Aus–Aman season and two NPK (87 kg N ha^{-1}) for the Boro season would be more profitable for southern Bangladesh. The FDP also provides the greatest benefits under rainfed wet season conditions where farmers have little control of water management and timing of N application.

Fertilizer nitrogen use efficiency (NUE) in rice cultivation is very low. The recovery of broadcast applied N by plant is generally 30 to 50% (Savant and Stangel, 1990). The low N use efficiency is attributed to ammonia volatilization, denitrification, leaching, and surface runoff. The N loss as ammonia volatilization from a flooded rice field can be as high as 50% of the applied N (Vlek and Craswell, 1979; Dong et al., 2012; Rochette et al., 2013). Broadcast application of PU resulted in higher amounts of ammonium N in floodwater compared to deep placement of urea (Kapoor et al., 2008). The higher the ammonium N in floodwater, the higher the ammonia volatilization loss will be (Rochette et al., 2013). Surface runoff is another important mechanism of nutrient loss from rice fields. Broadcast application of N, P, and K fertilizers increases the concentration of nutrients in floodwater (Kapoor et al., 2008). The nutrient-enriched runoff water can lead to a significant loss of N, P, and K and add the nutrient load in downstream water bodies, leading to eutrophication.

Because of the rising costs of production along with increased input costs including fertilizer, the quest for food security, and the need to mitigate environmental impacts, there is a need for improving management to deliver more efficient and balanced use of plant nutrients and to improve soil health. Fertilizer deep placement, particularly urea deep placement (UDP), in lowland rice fields has been widely recognized as an effective management practice for transplanted rice that increases productivity and reduces the amount of fertilizer use (Savant and Stangel, 1990; Gregory et al., 2010; Bandaogo et al., 2014). Deep placement of NPK at 7- to 10-cm depth reduces N, P, and K concentration in the floodwater; thus, it reduces N loss and increases uptake by the rice plant (Kapoor et al., 2008). Deep placement of urea or NPK increases NUE up to 50 to 70%, increases grain yield by 15 to 20%, and reduces fertilizer N use by 30 to 40% (Savant and Stangel, 1990; Alam et al., 2013; IFDC, 2013). However, the use efficiency varies across seasons and sites due to differences in soil and climatic conditions. In general, fertilizer response is higher during the dry season and in the soil with low indigenous nutrient supply. Accordingly, for site- and season- specific management, fertilizer rates were calculated based on indigenous soil nutrient supplies, plant nutrient demand and agro-ecological

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Abbreviations: BDT, Bangladeshi taka; FDP, fertilizer deep placement; LCC, leaf color chart; NPK, nitrogen–phosphorus–potassium briquette; NUE, nitrogen use efficiency; PPF$_N$, partial factor productivity for nitrogen; PU, prilled urea; UB, urea briquette; UDP, urea deep placement.

conditions (Witt and Dobermann, 2002). Nevertheless, deep placement of nutrients not only has a positive agronomic impact but also an environmental benefit by reducing the nutrient load in runoff water and reducing both volatilization and denitrification losses (Savant and Stangel, 1990).

In developing countries like Bangladesh where the government is providing more than 50% subsidies on fertilizers, saving fertilizer with efficient fertilizer management not only increases farm profitability but also saves the government fertilizer subsidy (IFDC, 2013). In Bangladesh, rice is grown two to three seasons per year on about 11 million hectares of land, which covers almost 80% of the total agricultural land. The three rice-growing seasons consists of Aus (May–August) and Aman (July–November), which are wet season rice mainly cultivated as rainfed crops, and Boro (January–May) rice, which is the dry season crop completely grown under controlled irrigated systems. On the rainfed rice-growing land in southern Bangladesh as well as many irrigated lands, especially tidal flood affected areas, there is no effective drainage system. Deep placement of N, P, and K in a single briquette could reduce their nutrient load in floodwater compared to surface broadcast and ensure continuous uptake by plants. Apart from the agronomic and environmental benefits, the deep placement of NPK eliminates the need to apply them separately, as is the standard practice, and consolidates the labor requirement compared to UDP and broadcast incorporation of P and K. Moreover, the use of NPK further provides opportunities for balanced fertilization. In tidal flood-affected areas, it is often not possible to follow the recommended schedule of split application of urea due to the risk of losses of surface-applied N; a good alternative may be the deep placement of either urea or NPK for a higher yield of rice. Therefore, we conducted the field experiments on famers' fields spreading across eight districts in southern Bangladesh to compare the effects of deep placement of urea or NPK over farmers' split broadcast application of N, P, and K fertilizers in terms of rice yield and farmers' income. In addition, selected treatments (UDP and broadcast PU) were evaluated on 440 demonstration plots in 2009–2010.

MATERIALS AND METHODS

Study Site and Weather Conditions

The field experiments were conducted in a continuous rice–rice–rice cropping system for nine consecutive seasons during 2009 to 2012 on farmers' fields. There are three rice-growing seasons (i.e., Aus, Aman, and Boro) in a year. Aus and Aman are monsoon seasons where rice is mainly grown as rainfed crop, while Boro is a dry season and crop production completely depends on irrigation water. The experiments were spread over 35 upazilas (subdistricts) of eight districts (Barisal, Bagerhat, Borguna, Jhalakati, Madaripur, Patuakhali, Pirojpur, and Shariatpur) in southern Bangladesh (22°14′–23°37′ N, 88°38′–90°27′ E). Shariatpur and Madaripur districts fall under agro-ecological zone (AEZ)-12 while the remaining districts fall under AEZ-13 (BBS, 2011). The region comprises an extensive area of tidal floodplain to the South and Southwest of the country. The climate is a humid subtropical monsoon. Average annual rainfall ranges from 1700 mm in the West to 3300 mm in the Southeast, primarily received from June to October. The entire region lies within the cyclone zone. In this region, soils are generally fertile silty clay with low to medium organic matter content, high acidity, high cation exchange capacity (CEC) and K, and low to medium Zn, B, and S (FRG, 2012).

Experimental Design and Treatments

A total of 115 field trials were established during nine rice-growing seasons over 4 yr. Out of 115 experiments, 31 experiments were established in 2009 (11 and 20 in Aus and Aman, respectively), 50 in 2010 (23, 16, and 11 in Boro, Aus, and Aman, respectively), 28 in 2011 (11, 7, and 10 in Boro, Aus, and Aman, respectively), and six in 2012 (Boro).

The four fertilizer treatments, namely broadcast PU (control), UB, and NPK of sizes 2.4 and 3.4 g (Table 1), were arranged in a randomized complete block design in each farmer's field (each farm represent a block). Farmers' fields were considered as replications. Out of four treatments, three treatments were deep placement of fertilizer briquettes and one was broadcast PU. Nitrogen rates for the Aus and Aman seasons were the same, while rates were higher during the Boro season. During the Boro season, urea briquettes of 2.70 g (78 kg N ha^{-1}, UB N78) were used instead of the 1.8 g (52 kg N ha^{-1}, UB N52) urea briquettes used during the Aus–Aman seasons. Similarly, two NPK of 2.4 g (87 kg N ha^{-1}, NPK N87) were used during the Boro season, while one briquette (43.5 kg N ha^{-1}, NPK N43) was used in the Aus–Aman seasons. Treatment with NPK of 3.4 g (57 kg N ha^{-1}, NPK N57) was the same for all the seasons.

Urea briquettes of 1.8 g (Aus and Aman) and 2.7 g (Boro) at 62,500 placement sites per ha (40 by 40 cm spacing) were

Table 1. Fertilizer treatments and nutrient rates used in the experiments during the Boro, Aus, and Aman seasons in southern Bangladesh. PU, UB, and NPK represent broadcast prilled urea, deep placement of urea briquettes, and NPK briquettes, respectively.

	Briquette wt.		N rate		P rate		K rate	
Treatment	Aus–Aman	Boro	Aus–Aman	Boro	Aus–Aman	Boro	Aus–Aman	Boro
			kg ha^{-1}					
PU	–	–	78	120	14	20	19.5	36
UB	1.8 (1)†	2.7 (1)	52	78	14	20	19.5	36
NPK	2.4 (1)	2.4 (2)	43.5	87	10	20	12.5	25
NPK	3.4 (1)	3.4 (1)	57	57	15	15	22	22
	Ratio of urea, diammonium phosphate (DAP), and muriate of potash (MOP) in NPK briquettes							
Briquette wt.	Urea	DAP	MOP	Urea	DAP	MOP		
g		Per briquette			Per 100 kg			
2.4	1.2	0.8	0.4	50	33.33	16.67		
3.4	1.5	1.2	0.7	44.12	35.3	20.59		

† Number in parenthesis represents briquette number per application site, briquettes were deep placed (7–10 cm) between alternate four hills of rice, PU was broadcast in three equal splits.

equivalent to 52 and 78 kg N ha^{-1}, respectively. The NPK of 2.4 and 3.4 g were prepared using PU, diammonium phosphate (DAP), and muriate of potash (MOP). The ratios of PU, DAP, and MOP are shown in Table 1. The P and K rates were lower in NPK compared to broadcast application. The equivalent N rates for 2.4 and 3.4 g NPK were 43.5 and 57 kg N ha^{-1}, respectively. The placement of two 2.4 g NPK resulted in an N rate of 87 kg N ha^{-1}.

In addition to field experiments, two fertilizer treatments (broadcast PU and deep placement of UB) were tested in 440 demonstration plots across eight districts during 2009–2010 (Table 2) to compare the grain yield between UDP and farmers' broadcast PU with farmers' management practice. Plot size for each treatment was 200 m^2. In each demonstration field, deep placement of urea briquettes and other cultural practices were similar with field experiments, while broadcast urea was applied in two to three splits (early tillering, maximum tillering, and panicle initiation stages) following farmers' management practice.

Crop Management

Rice seedlings (two to three per hill) of 20 to 30 (Aus), 25 to 35 (Aman), and 35 to 45 (Boro) d old were transplanted at 20 by 20 cm spacing. Prilled urea was applied as broadcast in three equal splits at basal, 25 to 30 d after transplanting (DAT) and 5 to 7 d before panicle initiation. Urea and NPK (one to two per placement site) were applied 5 to 7 d after transplanting. The briquettes were deep placed at a 7- to 10-cm soil depth between four alternate hills of rice. Phosphorus (triple superphosphate) and K (muriate of potash, MOP) fertilizers were applied basally in all the plots (except plots receiving NPK) during final land preparation at 14 to 19 kg P–K ha^{-1} during the Aus–Aman seasons and at 20–36 P–K ha^{-1} during the Boro season. All the other management practices were similar for all the treatments.

In farmers' fields during Aus and Aman seasons, PU was applied in two splits, 60% of total N at early tillering and 40% at late tillering stages. During Boro season it was applied in three splits, 40% at 10–15 DAT, 30% each during maximum tillering stage and 5 to 7 d before panicle initiation stage. The average (± SD) N rates for Aus, Aman and Boro seasons were 95 ± 14, 92 ± 9 and 124 ± 9 kg N ha^{-1}, respectively.

Rice Yield and Yield Parameter

Effective tillers (panicle) and grain yield (14% moisture content) from experimental plots were recorded at maturity from 1 and 5 m^2 area, respectively. Grain yield in each demonstration plot was recorded from two subsamples (10 m^2 each). Moreover, to evaluate the response of deep placement of UB compared to broadcast PU under farmers' management practices, crop cuts were done (as in demonstration plots) from 1395 farmers' fields across eight districts where farmers cultivated rice following both broadcast PU and deep placement of UB (Table 2). The harvest area was same for all the growing seasons and years.

Partial factor productivity for nitrogen (PFP_N) or an index of total economic outputs relative to the use of all N sources (indigenous soil N and applied fertilizer N) was calculated as kg grain yield per kg N applied (Olk et al., 1998; Ladha et al., 2005).

$$\text{Partial factor productivity for N } (PFP_N) = \text{kg grain/kg applied N}$$

Grain yield in each treatment was due to applied N plus indigenous N. Similarly, the average N rate in the respective district was used while calculating PFP_N in farmers' field crop cuts. Yield increment and nutrient savings due to FDP over broadcast PU were estimated. Net benefit in US$ per ha^{-1} was calculated based on partial budget analysis.

Table 2. Districts and number of demonstrations and farmers' field crop cuts in the Barisal region during the Boro, Aus, and Aman seasons in 2009–2010.

District	Boro 2009	Aus 2009	Aman 2009	Boro 2010	Aus 2010	Aman 2010
Demonstration plots						
Bagerhat	7	9	12	8	4	7
Borguna	8	10	15	2	16	10
Barisal	11	14	16	14	7	11
Jhalakati	4	4	5	7	4	4
Madaripur	8	8	11	15	2	6
Patuakhali	6	14	19	5	12	14
Pirojpur	8	23	17	3	15	7
Shariatpur	12	–	3	22		1
Total	64	82	98	76	60	60
Crop cuts at farmers' fields						
Bagerhat	–	23	15	35	8	48
Borguna	–	85	28	4	84	35
Barisal	–	39	33	60	31	32
Jhalakati	–	46	14	18	10	2
Madaripur	–	15	6	92	1	4
Patuakhali	–	126	85	8	59	64
Pirojpur	–	116	20	11	46	5
Shariatpur	–	–	2	73	5	6
Total	–	450	204	301	244	196

Data Analysis

The ANOVA of different response variables within a season was performed with a Generalized Linear Mixed Model (SAS analysis package) as shown in following equation:

$$Y = r + t + r \times t$$

where r is replication (farmers' field), t is treatment and $r \times t$ is the error term. Treatment was handled as fixed effect, while replication and error term were considered as random effect. Pairwise mean comparison of treatments was done with the LSD values at 5%. The grain yield between broadcast PU and deep placement of UB in demonstration plots and from farmers' field crop cuts were compared with t statistics at $p < 0.05$.

Cost of production was considered the same for all the treatments except for fertilizer cost, labor cost for fertilizer application and weeding. Man-days for deep placement were estimated from the time required for deep placement in farmers' fields. Gross return was estimated based on the farm-gate price of the paddy. Net return was used to evaluate the superiority of the fertilizer treatments.

RESULTS

Deep placement of UB and NPK increased grain yield significantly ($p < 0.05$) over broadcast PU in all seasons (Table 3). On the other hand, yields between UB and NPK were not significantly different. In NPK deep placement, increasing N rate from 43 to 57 kg N ha^{-1} did not increase grain yield in all seasons. The increase in grain yield in deep-placed treatments was positively correlated with increased effective tillers (Table 3).

The response of deep placement was consistent among the seasons. However, higher response was observed during the wet season (Aus and Aman) than during the dry season (Boro) (Table 3). On average, across the year, UB increased grain yields by 28, 21, and 17% over broadcast PU during the Aus, Aman, and Boro seasons, respectively. Similarly, NPK (Aus–Aman: 43.5 kg N ha^{-1}; Boro: 87 kg N ha^{-1}) increased yields by 30, 21, and 17% over broadcast PU in the Aus, Aman, and Boro seasons, respectively. The NPK 57N (one 3.4 g) produced similar yield to NPK 43N (one 2.4 g) in the Aus and Aman seasons. Similarly, yields were statistically comparable for NPK 57N and NPK 87N during the Boro season. Grain yield from several farmers' fields in demonstration plots and randomly sampled crop cuts showed similar trends, that is, UDP increased yield by 16 to 28% during the Aus–Aman seasons and by 15 to 21% during the Boro season (Table 4).

Overall, deep placement of UB saved urea by 30 to 35% and increased grain yield by 22% compared to broadcast PU. Similarly, deep placement of NPK (2.4 g) at 43.5 kg N ha^{-1} in Aus–Aman and 87 kg N ha^{-1} during Boro saved urea by 44 and 28%, respectively. Moreover, deep placement of one 2.4 g NPK (43.5 N) also saved P and K by 29 and 36%, respectively, during the Aus–Aman seasons.

Deep placement of both UB and NPK increased PFP$_N$ by almost double compared to broadcast PU. Within the NPK, treatments increase in N rate and decreased PFP$_N$, indicating that plants use N efficiently at lower dose. The magnitude of PFP$_N$ is higher in all fertilizer deep-placed treatments. Maximum efficiency of N was obtained with NPK at 43.5 kg N ha^{-1} in the Aus–Aman seasons and with

Table 3. Effects of fertilizer deep placement and broadcast PU on effective tillers or panicles, grain yield, and agronomic nitrogen use efficiency (PFP$_N$) during three rice-growing seasons in 2009 to 2012.

	Effective tillers			Grain yield			PFP$_N$‡		
Treatments	2009	2010	2011	2009	2010	2011	2009	2010	2011
	m^{-2}			Mg ha^{-1}			kg kg^{-1} N		
Aus									
PU-N78	336 ± 20b†	236 ± 12c	296 ± 29a	4.2 ± 0.1b	3.4 ± 0.2b	3.7 ± 0.2b	54 ± 2c	42 ± 3c	47 ± 2c
UB-N52	431 ± 21a	273 ± 20b	367 ± 33a	5.4 ± 0.2(23)a	4.5 ± 0.2 (36)a	4.6 ± 0.3 (25)a	104 ± 3b	84 ± 5b	88 ± 5ab
NPK-N43	418 ± 26a	282 ± 15ab	390 ± 35a	5.3 ± 0.1(25)a	4.7 ± 0.2 (45)a	4.5 ± 0.3 (22)ab	122 ± 3a	106 ± 5a	103 ± 8a
NPK-N57	479 ± 15a	292 ± 18a	359 ± 30a	5.3 ± 0.2 (21)a	4.6 ± 0.2 (46)a	4.3 ± 0.2 (18)ab	94 ± 3b	81 ± 3b	76 ± 4b
CV, %	5.3	9.5	7.2	8.1	10.8	7.3	8.3	11.5	9.7
Aman	2009	2010	2011	2009	2010	2011	2009	2010	2011
PU-N78	244 ± 12b	267 ± 10b	248 ± 9b	4.2 ± 0.2b	4.0 ± 0.1b	4.5 ± 0.1b	54 ± 2c	54 ± 2c	58 ± 2c
UB-N52	309 ± 15a	309 ± 21a	281 ± 26ab	5.2 ± 0.2 (27)a	4.9 ± 0.2(22)a	5.2 ± 0.1(15)a	101 ± 3b	95 ± 3b	99 ± 3b
NPK-N43	304 ± 16a	306 ± 16a	266 ± 15ab	5.2 ± 0.2 (27)a	4.9 ± 0.2(22)a	5.1 ± 0.2(14)a	118 ± 5a	113 ± 4a	117 ± 4a
NPK-N57	285 ± 36a	311 ± 27a	287 ± 18a	5.2 ± 0.5 (27)a	5.2 ± 0.2 (28)a	5.3 ± 0.1(18)a	92 ± 7b	91 ± 4b	93 ± 2b
CV, %	8.5	10.1	11.8	6.6	6.3	6.1	8.3	7.7	7.1
Boro	2010	2011	2012	2010	2011	2012	2010	2011	2012
PU-N120	323 ± 16b	330 ± 17a	407 ± 25a	6.3 ± 0.2b	6.7 ± 0.3a	7.0 ± 0.2 b	52 ± 2c	56 ± 2c	58 ± 3c
UB-N78	395 ± 16a	–	432 ± 37a	7.4 ± 0.3 (17)a	–	8.3 ± 0.4 (17)a	94 ± 3b	–	106 ± 5b
NPK-N87	409 ± 21a	393 ± 19a	455 ± 34a	7.6 ± 0.3 (21)a	7.5 ± 0.3 (13)a	8.5 ± 0.3 (17)a	88 ± 3b	87 ± 4b	97 ± 3b
NPK-N57	391 ± 18a	356 ± 20a	452 ± 33a	7.3 ± 0.3 (17)a	7.0 ± 0.3 (6)a	7.8 ± 0.3 (9)ab	128 ± 4a	124 ± 6a	137 ± 5a
CV, %	8.5	9.1	7.9	5.1	5.1	4.9	7.4	6.8	5.7

† Mean values ± standard error of mean. Within a column and season, means followed by the same letters are not significantly different by LSD at the 5% level.

‡ Partial factor productivity for nitrogen (PFP$_N$) = kg grain/kg applied N, values in parenthesis represent percentage increase in grain yield over broadcast PU.

57 kg N ha^{-1} in the Boro season (Table 3). Significantly higher PFP$_N$ was observed in UB compared to broadcast PU in demonstration plots as well as in farmers' crop cuts (Table 4).

Partial economic analysis indicated that deep placement of UB and NPK contributed higher benefits over broadcast PU in all seasons (Tables 5 and 6). Deep placement of NPK (2.4 g) had the maximum additional income in all rice-growing seasons. From an economic point of view, deep placement of one small size NPK (2.4 g) in both the Aus–Aman seasons and two small size NPKs in the Boro season appears to be more viable.

DISCUSSION

Deep placement of either urea or NPK increased grain yield ($p < 0.05$) over broadcast PU in all rice-growing seasons and years (Table 3). The grain yield results of several farmers' fields in demonstration plots as well as in randomly sampled farmers' field crop cuts (Table 4) confirmed the results from experimental fields. Increased grain yield with UDP is already well-documented (Alam et al., 2013; Bandaogo et al., 2014; Gregory et al., 2010; Mohanty et al., 1999; Savant and Stangel, 1990). Deep placement of UB in an anaerobic zone (7–10 cm) of the flooded soils makes ammonium N–that comes from

Table 4. Comparison of rice yield and partial factor productivity for nitrogen (PFP$_N$) between broadcast prilled urea (PU) and deep placement of urea briquette (UB) in demonstration plots and farmers' crop cuts in eight districts of Barisal region during three rice-growing season in 2009–2010.

		Grain yield						PFP$_N$					
		Boro		Aus		Aman		Boro		Aus		Aman	
District	Plot	PU	UDP†	PU	UDP	PU	UDP	PU	UDP	PU	UDP	PU	UDP
		Mg ha^{-1}						kg kg^{-1} N					
2009													
Bagerhat	Demo	5.1b‡	6.0a	4.2b	5.2a	3.0b	3.6a	45b	73a	50b	98a	35b	71a
	Crop cut			4.5b	5.5a	3.5b	4.2a			54b	105a	39b	82a
Borguna	Demo	5.0b	7.0a	3.5b	4.8a	4.64b	5.6a	40b	87a	44b	94a	62b	109a
	Crop cut			3.7b	5.0a	3.9b	4.8a			45b	96a	53b	91a
Barisal	Demo	5.1b	7.0a	3.7b	4.6a	4.6b	5.5a	40b	86a	38b	89a	48b	107a
	Crop cut			3.5b	4.4a	4.2b	4.9a			35b	85a	43b	95a
Jhalakati	Demo	5.8b	7.8a	3.5b	4.8a	4.0a	4.8a	52b	98a	20b	93a	48b	93a
	Crop cut			3.6b	5.0a	3.6b	4.6a			20b	97a	44b	89a
Madaripur	Demo	6.5b	7.9a	4.5a	6.0a	3.4a	4.3a	52b	100a	50b	108a	33b	82a
	Crop cut			4.2a	5.0a	3.7b	4.5a			44b	89a	33b	86a
Patuakhali	Demo	4.8a	5.8a	3.3b	4.3a	4.1b	5.1a	40b	72a	39b	83a	58b	100a
	Crop cut			3.1b	4.2a	3.8b	4.7a			36b	81a	53b	92a
Pirojpur	Demo	4.2a	5.0a	3.8b	5.8a	3.3b	4.0a	38b	64a	35b	104a	34b	78a
	Crop cut			4.1b	5.6a	3.5b	4.3a			36b	100a	35b	81a
Shariatpur	Demo	6.4b	8.0a	–	–	2.5a	2.9a	40b	100a	–	–	26b	56a
	Crop cut			–	–	3.2b	3.6a					32b	69a
Mean	Demo	5.4b	6.8a	3.8b	5.1a	3.8b	4.8a	43b	86a	40b	96a	46b	91a
	Crop cut			3.7b	4.9a	3.8b	4.6a			37b	92a	47b	90a
2010													
Bagerhat	Demo	5.5a	6.6a	3.4a	3.9a	3.7b	4.5a	49.7b	82a	42b	75a	35b	88a
	Crop cut	5.6b	6.5a	3.6b	4.2a	3.5b	4.2a	50.6b	81a	43b	81a	33b	82a
Borguna	Demo	4.4a	5.0a	3.9b	4.6a	4.5b	5.4a	38.1b	64a	41b	90a	42b	104a
	Crop cut	4.6a	5.5a	3.6b	4.4a	5.2b	5.9a	40.3b	71a	39b	84a	47b	113a
Barisal	Demo	5.9a	6.8a	3.3b	4.1a	3.9b	4.6a	49.7b	88a	37b	79a	41b	89a
	Crop cut	5.8b	6.7a	3.2b	4.0a	4.0b	4.7a	46.7b	87a	35b	77a	44b	92a
Jhalakati	Demo	6.5b	7.3a	3.8a	5.2a	4.9a	5.5a	64.1b	94a	56b	101a	48b	106a
	Crop cut	6.3b	6.9a	3.4b	4.0a	3.8a	4.6a	62.0b	89a	50b	77a	37b	88a
Madaripur	Demo	5.7b	6.7a	3.5a	4.1a	4.3b	5.4a	43.5b	86a	38b	80a	41b	105a
	Crop cut	5.9b	6.7a	3.7	4.0	4.3a	5.4a	43.6b	86a	37	78	38b	104a
Patuakhali	Demo	4.4a	5.3a	3.5b	4.3a	4.4b	5.2a	36.5b	68a	44b	84a	44b	100a
	Crop cut	5.4b	6.3a	3.1b	3.9a	4.6b	5.4a	44.8b	81a	38b	74a	46b	104a
Pirojpur	Demo	4.9a	6.7a	4.0b	4.7a	4.0b	4.7a	38.4b	85a	44b	91a	39b	91a
	Crop cut	5.6b	6.6a	3.9b	4.7a	3.7a	4.2a	42.7b	83a	42b	90a	35b	81a
Shariatpur	Demo	6.1b	7.3a	–	–	2.4	3.2	51.6b	93a	–	–	21	63
	Crop cut	6.5b	7.5a	2.6a	3.1a	3.5a	4.6a	54.0b	95a	29b	59a	31b	77a
Mean	Demo	5.8b	6.8a	3.7b	4.5a	4.2b	5.0a	48.7b	87a	43b	87a	41b	96a
	Crop cut	6.0b	6.9a	3.5b	4.2a	4.3b	5.0a	48.6b	88a	39b	81a	42b	97a

† UDP, urea deep placement.

‡ Within a row and season, means followed by the same letter are not significantly different at 0.05 level of probability by *t* test.

Table 5. Prices of inputs and outputs and rates used for calculating cost of production and profits in different treatments for conducting partial economic analysis.

Particulars†,‡	Aus 2009	Aman 2009	Boro 2010
Rice sale price, BDT kg^{-1}	14	14	17
Labor wages, BDT person-d^{-1}	200	200	250
Fertilizer cost, BDT kg^{-1}			
Urea	12	12	12
Urea briquette	14	14	14
NPK briquette, 2.4 g	27	27	24
NPK briquette, 3.4 g	27	27	24
DAP	45	45	30
TSP Urea	22	22	22
MOP Urea	25	25	25
Fertilizer application cost, BDT season^{-1}			
Urea broadcast	400	400	500
Briquette, one NPK or urea briquette	2200	2200	2200
Briquette, two NPK briquettes	–	–	2450
Weeding cost, BDT season^{-1}			
Broadcast urea	6000	4500	4500
Deep placement	3000	2250	2250

† Other inputs not mentioned here are considered the same for all the treatments.

‡ BDT, Bangladeshi taka; DAP, days after planting; TSP, triple super phosphate; MOP, muriate of potash.

hydrolysis of urea–more available and stable because of reduced ammonia volatilization loss and nitrification. The diffusion of ammonium N from the anaerobic zone to the surface soil is very slow (Rochette et al., 2013). This is evident from negligible N in floodwater in deep-placed treatments; thus, N losses from ammonia volatilization and surface runoff are reduced (Kapoor et al., 2008; Vlek and Craswell, 1979). Deep-placed N may remain in the root zone for a longer time and ensure continuous supply of N for plant growth and development throughout the crop growth period, resulting in increased NUE (Cao et al., 1984). Continuous supply of N increases the number of effective tillers (Table 3), which further increases N uptake; hence, it increases grain yield as well. In contrast, if the ammonium is oxidized, as occurs when urea is broadcast, it converts to nitrate and is lost through further denitrification and surface runoff. The higher response of deep placement on grain yield during the Aus–Aman seasons than during the Boro season is probably due to increased surface runoff losses of N with monsoon rain in broadcast PU plots than in deep-placed treatments. But during the Boro season, irrigation water is controlled during fertilizer application and surface runoff is minimized; thus, crop response to PU is higher than it is during the Aus and Aman seasons.

However, the performance of UDP relative to broadcast PU depends on the management practice of PU, that is, the timing and frequency of its applications. Alam et al. (2013) compared yields and economic returns of UDP and broadcast PU application with the leaf color chart (LCC) across different districts in Bangladesh under farmers' crop management practice for five rice-growing seasons. The grain yields and economic returns were similar between UDP and PU with the LCC, suggesting that the real time N management, that is, synchronizing N application with plant need, can increase NUE. Split applications may enable farmers to adjust the times and doses of fertilizer application unlike one-time investment for deep placement. Controlled-release N fertilizers with improved synchrony of N supply and crop N demand are very effective in increasing NUE; however, they are not profitable for field crops. During the Boro seasons or when multiple N split applications can be managed as determined by LCC, the LCC approach can be as effective as UDP. Both LCC and UDP led to higher grain yield and net return compared to farmers' practice (Alam et al., 2013). The choice of LCC or UDP may depend on the farmer's level of knowledge, availability of labor, availability of briquettes, type of soil, and water management.

Table 6. Effects of broadcast prilled urea (PU) and deep placement of urea and NPK briquettes on partial economics of rice production during the Aus, Aman, and Boro seasons during 2009–2010 in southern Bangladesh.

	Production cost‡			Gross return			Net income		
Treatment†	Aus	Aman	Boro	Aus	Aman	Boro	Aus	Aman	Boro
	US$ ha^{-1}								
Broadcast PU	142	127	157	753	778	1377	610	651	1219
UB§	121	114	140	947	964	1610	827	849	1469
NPK, 2.4 g	120	110	154	953	962	1656	833	851	1501
NPK, 3.4 g	142	132	124	969	953	1572	827	821	1448

† Fertilizer rates vary among rice-growing seasons (see Table 1).

‡ US$1 = 77 Bangladeshi taka, BDT.

§ UB, urea briquette.

Nevertheless, benefits of UDP are not only limited to the farmers. It provides profitable business opportunities for local entrepreneurs or fertilizer dealers and contributes to local economic development. In Bangladesh, net returns to dealers who manufacture briquettes average about \$1 per 50 kg PU. The UDP has national benefits because of less imports or production of PU that saves cost of government fertilizer subsidies. Urea deep placement also has environmental benefits because it significantly reduces N losses from the soils including nitrous oxide emissions (Gaihre et al., 2015) and reduces groundwater and water-way contamination (IFDC, 2013). However, surface run-off losses in the farmers' fields are predicted based on the amount of ammonium N present in floodwater after broadcast application of PU. More studies are needed for actual quantification of run-off losses from rice fields.

Higher grain yield with deep placement of NPK may also be attributed to less nutrient losses and efficient utilization of applied P and K in addition to N, as in UDP (Kapoor et al., 2008). Previous studies have reported increased grain yield with multinutrient fertilizer briquettes (Daftardar et al., 1997; Kapoor et al., 2008). Daftardar et al. (1997) conducted 77 adaptive research trials in different farmers' fields in India during the 1993 and 1994 wet seasons using urea-DAP (NP) briquettes. They observed that NP briquettes increased grain yield by 45 to 89% over farmers' practice and by 27 to 52% over recommended management practice. Deep placement of urea, NP, and NPK had significantly higher yield than broadcast split application of PU, DAP, and MOP in greenhouse condition (IFDC, unpublished data, 2008–2011). In this study, deep placement of both urea and NPK significantly increased PFP_N compared to broadcast PU (Table 3). Moreover, deep placement of NPK had much higher N recovery (88–93%) compared to UDP (66%) and broadcast PU (46%) (Aslam et al., 2011). In addition to increased N recovery, the improved N use efficiency in deep-placed treatments could be due to increased grain yield and less N fertilizer use. However, the effects of lower rates of P and K with deep placement on long-term balance of P and K in soil are not yet clear. The rates should be based on soil fertility and crop demand to ensure correct balance and to avoid nutrient mining.

In NPK treatments, particularly during the Aus and Aman seasons, higher PFP_N was observed at lower N rates (43.5 kg N ha^{-1}) than at higher rates (57 kg N ha^{-1}). Though both sizes of NPK resulted in similar grain yield, use of 2.4 g briquettes reduced the amount of fertilizer compared to UDP (43 vs. 52 kg N ha^{-1}). The net economic returns in deep placement of NPK (2.4 g) were 20 to 30% higher than broadcast urea in all the seasons, while deep placement of either UB or NPK provided similar net income. Since most of the farmers do not use balanced fertilization, deep placement of NPK offers potential for higher yields and improved fertilizer use efficiency because of balanced fertilization and reduced nutrient losses.

Moreover, there are also environmental benefits arising from a lower nutrient load in runoff water and reduced emissions of greenhouse gas due to deep placement of NPK fertilizer. Apart from the agronomic and environmental benefits, the deep placement of NPK would consolidate labor requirements compared to UDP and broadcast incorporation of P and K. In the tidal flood-prone areas of southern Bangladesh, there is a high risk of nutrient loss through surface runoff when applied as broadcast. Considering grain yield, PFP_N, and net economic return, FDP is a promising management option to increase rice productivity and farm income. Fertilizer deep placement also provides the greatest benefits to farmers under rainfed wet season conditions where farmers have no or little control on water management and timing of N application. Deep placement, in addition to lowland rice, also performed better in aerobic rice (Xiang et al., 2013) and upland crops such as potato (*Solanum tuberosum* L.) (Azam et al., 2012) and cabbage (*Brassica oleracea*) (Hussain et al., 2010), showing the potential of UDP adoption on upland crops.

Though deep placement of fertilizer briquettes requires more labor cost compared to broadcast PU, reduced cost in fertilizer and weeding and increased grain yield provided higher economic returns (Table 6). Increased labor cost for deep placement and reduced cost for weeding observed in this study were consistent with previous studies conducted in different districts of Bangladesh (Gregory et al., 2010; Thompson and Sanabria, 2010). Other intercultural practices such as transplanting, irrigation, plant protection measures, harvesting etc., were considered equally for both broadcast and deep-placed treatments. Therefore, differences in fertilizer cost including its application and weeding cost were considered for economic comparison. However, considering the cost of intercultural practices such as deep placement of briquettes, weeding may vary from location to location depending on the working efficiency of laborers (Thompson and Sanabria, 2010). Due to increased labor outmigration from the agriculture sector to other sectors, deep placement should be mechanized for the wider adoption of FDP technology. Recently, scientists from national agricultural research organizations (NARO) in Bangladesh have developed mechanized applicators suitable for small holder farmers (Hoque et al., 2013; Ahamed et al., 2014), and applicators are already available to the farmers of some selected districts. Wider adoption was mainly limited mainly due to lack of availability of fertilizer briquettes and low-cost applicators. Availability of the briquettes has been significantly increased with the intervention of public-private partnerships in fertilizer briquette production and marketing (IFDC, 2013). Therefore, access of efficient mechanized applicators to the farmers may significantly reduce labor cost and increase adoption.

CONCLUSIONS

The results from the field experiments, demonstration plots, and farmers' field crop cuts clearly showed that the deep placement of either urea or NPK increased grain yields significantly compared to broadcast PU. Across the years, deep placement of NPK at 43.5 kg N ha^{-1} (Aus–Aman) and 87 kg N ha^{-1} (Boro) increased grain yield by 31, 21, and 17% over broadcast PU during Aus, Aman, and Boro, respectively. Grain yields were statistically similar ($p > 0.05$) with the deep placement of NPK and urea briquettes. At the same time, deep placement decreased the amount of fertilizer needed by 30 to 45% over broadcast PU. Deep placement significantly increased PFP_N compared to PU. In NPK, however, increasing N rate from 43 to 57 kg ha^{-1} during the Aus–Aman seasons significantly decreased $PFP_{N,}$ probably because factors other than N such as solar radiation may have limited grain yield. The higher grain yield with UB compared to PU was confirmed from numerous demonstration plots and farmers' field crop cuts. Similarly, with grain yields, higher net returns were obtained with FDP treatments over broadcast PU. Deep placement of NPK at 43.5 kg N ha^{-1} (one 2.4 g per application site) for the Aus and Aman seasons and 87 kg N ha^{-1} (two 2.4 g per application site) for the Boro season could be one of the options to increase grain yield and farm income in the tidal flood-prone areas of southern Bangladesh.

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