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Urea briquettes combined with a fertilizer blend reduces fertilizer costs and improves yields of irrigated rice in Rwanda

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Abstract

We evaluated the yield and potential economic impact in Rwanda of replacing the standard lowland rice (*Oryza sativa* L.) fertilizer recommendation from the current practice of 200 kg NPK 17-17-17 ha^{-1} and 100 kg urea ha^{-1} with a basal blend of 74 kg diammonium phosphate (DAP), 57 kg potassium chloride (KCl), and deep placement of 112.5 kg urea briquettes ha^{-1} at 4 weeks after transplanting. Experiments were carried out in nine diverse marshlands across Rwanda in the long and short rainy seasons of 2016, with the two fertilizer treatments and a no-fertilizer control. Compared to the current practice, the urea deep placement (UDP) package increased yields by 1.08 and 0.84 mt ha^{-1} in the respective seasons, while at the same time lowering N fertilizer rate by 15 kg ha^{-1}. Average value to cost ratio increased from 1.89 (current recommendation) to 3.16 (UDP recommendation) and would be still greater than 2.0 at six times increase in labor cost. The cost of fertilizer recommendation (fertilizer cost plus application cost) was lower with the UDP package due to replacing 17-17-17 with a lower rate of the DAP and KCl combination. The overall average net benefit of US$300 ha^{-1} was substantial. Should labor cost increase by eight times compared to the current $1.52 per person-day, UDP would still provide a benefit of $150–$207 ha^{-1} compared to the current practice. On a national scale, converting to the UDP package recommendation would result in additional 32,000 mt rice and increase farmer revenue by some US$10 million annually.

1 | INTRODUCTION

Nitrogen (N) is an essential nutrient for rice production, and its deficiency is a major cause of sub-optimal production (Hasanuzzaman et al., 2009). On average, 1 kg of N increases the yield of paddy rice from 15 to 20 kg (Peng et al., 2006). Urea is the most widely used N fertilizer in rice production, and farmers tend to apply it abundantly. Much of the applied urea is lost into the environment. Only 30% to 50% of applied urea in paddy rice is used by plants, while 50% to 70% remains in the soils or is lost in the environment through ammonia and nitrous oxide (NO_x) volatilization, denitrification, leaching, and surface runoff (Miah et al., 2016). Pollution

Abbreviations: BCR, benefit to cost ratio; DAP, diammonium phosphate; GHG, greenhouse gas; GPS, global positioning system; KCl, potassium chloride; NB, net benefit; NPK 17-17-17, nitrogen, phosphorus, and potassium fertilizer compound; UDP, urea deep placement; VCR, value to cost ratio.

of the environment with N lost from rice paddy fields leads to water eutrophication, groundwater pollution, greenhouse gas (GHG) emissions, and soil acidification (Chen et al., 2020). Increasing nitrogen recovery both increases productivity and profitability while decreasing the environmental damage caused by rice production.

In 2021, estimates for paddy rice in Rwanda were 15,840 ha for cultivated area, 4.2 t ha^{-1} for average yield and 65,879 mt for total grain production per season for the two rice seasons (NISR, 2021). Technologies for efficient management of urea in rice production have been developed, including split or multiple applications of urea, urea deep placement (UDP), and controlling the release of urea by coating it with resin or polyurethane (Chen et al., 2020). These technologies increase fertilizer use efficiency, productivity, and reduce emissions of nitrous oxides, ammonia, and methane. However, farmer adoption of some technologies has been limited due to cost considerations or increased labor demands (Chen et al., 2020; Guo & Wang, 2021).

UDP consists first of compacting urea into large granules, typically between 1.5 and 3.0 g each. These granules are then placed deep into the soil at regular intervals at a depth between 5 and 10 cm, either manually or by use of a mechanical applicator. Typically, briquettes applied to rice spaced at 20 × 20 cm are placed at intervals of 40 × 40 cm, with one briquette applied between four rice plants. Whereas broadcast urea rapidly dissolves in surface water and is subject to multiple mechanisms of loss, deep-placed urea granules are slowly converted to ammonium in the soil, resulting in a gradual release more synchronous to rice uptake. Surface-applied urea is also more likely to be taken up by shallow weeds. UDP tends to remain in less leachable ammonium form, diffusing gradually from the point of placement and more in synchrony with rice requirements (Gaudin, 1988; Rochette et al., 2013). UDP, being concentrated in a small volume below the soil surface relative to broadcast urea, is less likely to suppress the growth of blue-green algae that fixes atmospheric N (Roger et al., 1980; Wada et al., 1986). UDP extends the period of N release by 2 months or even longer, thus improving N use efficiency and yields (Chen et al., 2020). UDP reduces emissions of nitrogen oxides, one of the GHGs emitted from rice marshlands (BRRI, 2021; Gaihre et al., 2015; Yao et al., 2017), increases the profitability of rice production, and reduces expenditure on urea fertilizers (IFDC, 2007; IFPRI, 2004).

UDP has been successfully promoted in several Asian countries, particularly in Vietnam and Bangladesh (IFDC, 2007), resulting in average yield increases of 15%–20% and N use efficiency by 33% (Miah et al., 2016). Urea briquettes can be placed by hand into the soil (Bowen et al., 2004). This study was conducted in farmers' fields with the aim of evaluating effect of UDP on yield, growth characteristics, and profitability of rice in comparison to the current fertilizer recommendation involving broadcast urea. The UDP fertilizer package we tested not only includes UDP, but also replaces the basal application of 200 kg ha^{-1} NPK 17-17-17 with 74 kg diammonium phosphate (DAP) ha^{-1} and 57 kg potassium chloride (KCl) ha^{-1}. This is an important part of the fertilizer package, as it maintains the same P and K application rates while considerably reducing the volume and cost of the fertilizer applied.

Core Ideas

- Urea deep placement (UDP) package increased the height, number of tillers, and straw yield of rice.
- UDP package increased rice grain yield compared to current fertilizer broadcasting.
- UDP package is more profitable than current fertilizer broadcasting.
- Profitability of UDP package is not compromised by increasing labor cost with time.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

Experiments were established in nine marshlands in Rwanda during February to June 2016 season and September 2016 to February 2017 seasons, referred to in Rwanda as the 2016B and 2017A seasons, respectively (Nabahungu et al., 2020). The marshlands are in Eastern province (Muvumba, Cyabayaga, Kanyonyomba, Cyaruhogo, and Cyunuzi), Southern province (Rwasave, Rugeramigozi, and Mukunguri), and Western province (Bugarama) in Rwanda (Figure 1).

2.2 | Soil sampling and analysis

Five composite samples made of five cores were collected from each of the five experimental plots within a marshland and thoroughly mixed to form one composite sample per marshland. Each composite sample was then analyzed before planting in 2016B season. Proportions of soil particle sizes were analyzed using the hydrometer method, soil pH was measured using a pH meter at 1:2.5 soil/water ratio, phosphorus was extracted using Bray 1 solution and determined by a colorimeter, exchangeable K was extracted by 1 M ammonium acetate and measured by a flame photometer, exchangeable aluminum was determined through extraction with 1 M KCl and back titration method, electric conductivity was determined by saturation methods and read using EC meter, cation exchange capacity (CEC) was determined using ammonium acetate and KCl solution and colorimetric method, and soil organic matter was estimated

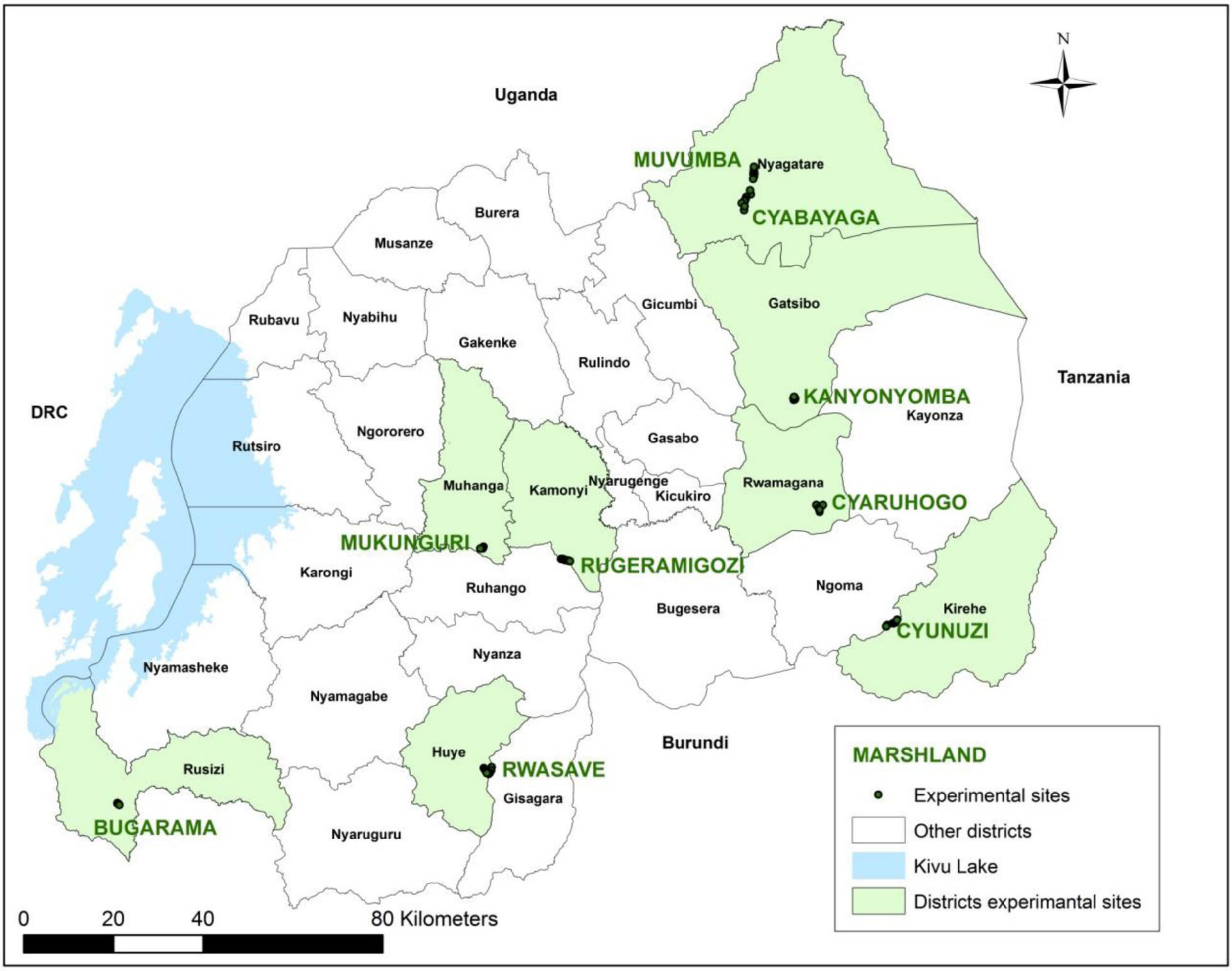

FIGURE 1 The location of study sites in Eastern, Southern, and Western provinces in Rwanda. The rainfall pattern is bimodal with two rainy seasons: the short rain season from September to February, referred to as season A, and the long rain season from February to June referred to as season B (Global Rice Science Partnership, 2013). The mean annual rainfall varies between 800 and 1400 mm (Nabahungu & Visser, 2011; Verdoodt & Van Ranst, 2003).

by wet oxidation with both potassium dichromate and concentrated sulfuric acid and titration with ferrous ammonium sulfate. Soils from the nine marshlands had a sandy clay loam texture. The site global positioning system (GPS) coordinates, elevations, soil types, and soil physical and chemical characteristics are shown in Table 1.

2.3 | Experimental design, management of trials, and fertilizer treatments

Marshlands were selected based on existence of well-maintained irrigation systems and well-organized farmer cooperatives that owned machines to make briquettes. Within a marshland, five farmers were selected, allowing a distance of at least 100 m between two farmers. In the marshland, the experiment followed a randomized block design. A farmer site was considered a block or a replication. Each farmer hosted a set of three plots corresponding to three treatments: no fertilizer, the current farmer practice of 200 kg ha^{-1} of NPK 17-17-17 fertilizer followed by a top-dress of 100 kg ha^{-1} of urea, and the UDP package consisting of 73.9 kg ha^{-1} DAP, 56.7 kg ha^{-1} of KCl, and 112.5 kg urea briquettes. The rates of DAP and KCl in the UDP treatment package were chosen to supply the same amount of P and K as the current urea broadcast recommendation, while the briquette rate is based on the application of 1.8 g briquettes deep placed at intervals of 40 × 40 cm. The size of each treatment plot was 5 × 5 m, and plots were separated by bunds of 1 m width to avoid fertilizer moving between treatments. The rates of fertilizer nutrients were 80 kg N, 34 kg P_2O_5, and 34 kg K_2O ha^{-1} for the urea broadcast treatment, and 65 kg N, 34 kg P_2O_5, and 34 kg K_2O ha^{-1} for the UDP treatment.

Experimental fields were prepared 10 days before transplanting using hand hoes. The Yun Keng variety was used at all sites. Seedlings were prepared by soaking seeds in water for 24 h, placing them in gunny bags to sprout, and placing them in a nursery seedbed after 72 h. Transplanting

TABLE 1 Site characteristics of nine marshlands used.

Marshland	Latitude (˚)	Longitude (˚)	Elevation (m)	Rainfall (mm)	Soil classification
Bugarama	2.6803	29.0061	987	1226	Eutric Vertisols
Cyabayaga	1.4074	30.2769	1360	904	Eutric Vertisols
Cyaruhogo	2.0297	30.4189	1344	756	Mollic Gleysol
Cyunuzi	2.2742	30.5560	1332	1267	Terric/Fibric Histosols
Kanyonyomba	1.7740	30.3729	1469	972	Eutric Vertisols
Mukunguri	2.1399	29.9247	1985	1009	Dystric (Humic) Cambisols/Haplic (Humic) Alisols
Muvumba	1.2597	30.3342	1342	1000	Eutric Vertisols
Rugeramigozi	2.1126	29.7478	1787	1251	Dystric (Humic) Cambisols/Haplic (Humic) Alisols
Rwasave	2.6102	29.7639	1631	1046	Dystric (Humic) Cambisols/Haplic (Humic) Alisols

Marshland	pH (1:2.5 water)	Bray P (mg kg^{-1})	Exch. K (mg kg^{-1})	Electrical conductivity (µS cm^{-1})	Exch. Al (mg kg^{-1})	CEC (mg kg^{-1})	Organic matter (g kg^{-1})	C/N
Bugarama	7.1	5.4	130	297	0.0	47.2	65	17.1
Cyabayaga	5.4	17.8	124	260	0.4	25.1	57	12.9
Cyaruhogo	5.3	10.5	94	423	0.2	26.9	55	11.1
Cyunuzi	5.1	1.1	58	561	0.2	32.0	70	7.0
Kanyonyomba	5.3	12.7	100	448	0.0	23.6	38	13.4
Mukunguri	5.5	10.0	153	96	0.1	13.9	36	10.2
Muvumba	5.0	56.0	268	153	1.0	25.6	61	14.6
Rugeramigozi	4.9	5.1	47	236	1.1	16.8	66	11.2
Rwasave	5.1	3.6	28	140	0.5	12.7	60	15.3

in experimental plots occurred approximately 45 days after planting in nurseries. As per Rwanda current farmer practice, seedlings were planted at a spacing of 20 cm between rows and 20 cm within rows and placing two seedlings per hill. Gaps were filled 1 week after transplanting. Experimental plots were kept free from weeds by weeding three times in a season. No remarkable infestation of insect pests or diseases was observed during the study period.

For the two fertilized treatments, basal fertilizers (either NPK 17-17-17 or DAP + KCl) were broadcast at planting. For the current farmer practice fertilizer treatment, top-dress granular urea was broadcast as two split applications of 50 kg ha^{-1} each, approximately 40 and 60 days after transplanting. For the UDP treatment package, briquettes were applied at approximately 4 weeks after transplanting by manually pressing the briquettes into the soil to a depth of approximately 7 cm at the spacing previously described.

2.4 | Monitoring growth and productivity

At 90 days after planting, five hills of plants were randomly selected in each treatment plot, from which average plant height and number of tillers were determined. Plant height was measured from the base to the tip of the highest leaf. At maturity, when 80% of the grains turned golden yellow in color, the net plot was harvested, with two extreme rows and two plants at both ends of each row eliminated to avoid the edge effect. Harvesting was done by cutting plants at some 2 cm above the ground and threshing them using a hand thresher. Paddy grains were air dried to a constant weight and assessed for moisture content. Paddy grain weight was adjusted to 14% moisture content to estimate yield per hectare. Straw was sun dried to a constant weight and weighed to estimate straw dry matter yield per hectare.

2.5 | Economic and statistical analysis

Three economic indicators were calculated: the value to cost ratio (VCR), the benefit to cost ratio (BCR), and the net benefit (in US$ ha^{-1}) of changing from the current practice of broadcasting urea to the UDP package alternative. The VCR is the value of incremental yield compared to plots without fertilizer, divided by costs related to the fertilizer treatment, which includes fertilizer purchase cost, cost of labor to apply fertilizers, and cost to harvest and transport added harvest compared to the control plot. It was calculated using Equation (1).

$$\mathrm{VCR} = \left[\left(Y_i - Y_\mathrm{o}\right) \times P_\mathrm{r} / \left(C_\mathrm{f} + C_\mathrm{a} + C\Delta h\right)\right] \quad (1)$$

where VCR is the value to cost ratio, Y_i is the rice yield of a treatment in kg per ha, Y_o is the yield in kg per ha for the control treatment (without fertilizer), P_r is the price of one kg of paddy rice paid to rice growers at harvest, C_f is the cost per ha of the fertilizers, C_a is the cost of fertilizer application, and $C\Delta h$ is the differential costs associated with harvest and post-harvest between the control and fertilized treatment plots, and labor to transport to the drying area and winnow the harvest, with all costs having units of US$ per ha. The labor required to transport harvest to the processing area and the labor required to winnow the harvest are estimated to be, respectively, 1 person-day and 1.67 person-days per mt of harvested rice. Therefore,

$$C\Delta h = 2.67L \times \left(Y_i - Y_o\right) \quad (2)$$

where L is the labor cost in United States dollars (US$) per person-day.

The BCR is a measure of the return to investment in mineral fertilizers. It is the net benefit (NB from Equation 3; the value of the production minus costs related to fertilizers, i.e., the total cost of purchasing and applying mineral fertilizers; Equation 3) divided by costs related to fertilizers (total cost of purchasing and applying mineral fertilizers). The BCR is calculated using Equation (4).

$$\text{NB} = \left(Y_i \times P_r\right) - \left(C_f + C_a + C\Delta h\right) \quad (3)$$

$$\text{BCR} = \text{NB}/\left(C_f + C_a + C\Delta h\right) \quad (4)$$

All parameters were calculated based on farm gate prices. The farm gate price of rice was 0.279 US$ per kg of paddy rice and was sourced from rice farmers in the study marshlands. The cost of mineral fertilizers was sourced from the Ministry of Agriculture and Animal Resources (MINAGRI) and was 0.94 US$ kg^{-1} NPK fertilizer (NPK 17–17–17), US$1.056 kg^{-1} DAP, 0.788 US$ kg^{-1} KCl, US$0.882 kg^{-1} urea, and US$0.913 kg^{-1} urea briquettes. Estimation of cost of applying mineral fertilizers was based on farmers' experience in broadcasting urea and placing urea briquettes deep in the soil. They estimated that 4 person-days per ha are required to broadcast urea (2 person-days per ha times two applications), while 13 person-days per ha are required to place briquettes of urea into the soil. Basal fertilizer application was estimated to require 2 person-days per ha. The cost of one person-day was US$1.516 across study marshlands. Costs related to purchasing and applying mineral fertilizers were calculated at zero for no fertilizer plots, US$285.3 ha^{-1} for plots with broadcast urea, and US$248.2 ha^{-1} for the UDP package treatment.

The net benefit for changing from the current urea broadcast practice to UDP package was calculated from the difference of the net benefit of UDP package and the net benefit for broadcast urea (both determined from Equation 3).

The economic analysis employed a partial budget analysis where only variable costs are considered (Alimi & Manyong, 2000; CIMMYT, 1988). Variable costs were fertilizer costs (purchasing and application) and costs related to transport to the drying area and winnowing. Labor costs due to planting, weeding, harvesting, threshing, and drying were considered as non-variable costs. Technologies are considered likely for adoption when their BCR and VCR are greater than 2.0 (Kelly & Murekezi, 2000; Kihara et al., 2015).

Since briquette application requires more labor than broadcasting urea (15 vs. 6 person-days ha^{-1} for the respective application methods, including basal fertilizer application) a sensitivity analysis of the VCR to labor costs for both applications was performed. The VCRs were calculated at labor costs of $1.50, $3, $6, $9, and $12 per person-day for each marshland in the study, averaged over the two seasons for each marshland. Additionally, the net benefit to UDP versus the current practice of broadcast urea was calculated based on the same labor costs and averaged over the marshlands for the two seasons.

Data analysis was done for each of the two seasons, separately. Fertilizer type (treatment), marshland, and their interaction were considered the main factors while replications in marshlands were fitted as random factors. Plant height, number of tillers per plant, paddy grain yield and straw yield, VCR and BCR were analyzed using a general linear model. Mean separation was done using the least significant difference method at $p < 0.05$. All statistical analyses were done in R version 3.6.3 (R Core Team, 2020).

3 | RESULTS

3.1 | Effect of UDP package on growth parameters

The UDP package increased the number of tillers, plant height, above-ground biomass, and yield in both seasons compared to broadcast urea (Tables 2 and 3). Statistical analysis showed that for all parameters and seasons, marshland and treatment were highly significant ($p < 0.0001$), but that there was no interaction between marshland and treatment, except for yield in 2016B. On average, the UDP package treatment increased the number of tillers per plant by 3.5 and plant height by 6.6 cm compared to the traditional practice of urea broadcasting. On average, paddy rice yields in the UDP package treatment increased by 0.97 mt ha^{-1} and straw biomass by 0.86 mt ha^{-1} when compared to broadcasting urea. Highest average yields were obtained in the Bugarama marshland and lowest yields in Rugeramigozi, which reflects their relative fertility status (Table 1).

TABLE 2 Effects of urea treatment on number of tillers per plant and plant height.

Source of variation	Number of tillers	Plant height	Above-ground biomass	Rice (paddy) yield	VCR	BCR	Net benefit of UDP versus broadcast urea
2016B							
Treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
Marshland	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.053
Treatment × marshland	0.83	0.83	0.99	0.01	0.28	0.36	
2017A							
Treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
Marshland	<0.0001	<0.0001	<0.0001	<0.0001	0.079	0.079	0.137
Treatment × marshland	0.74	0.85	0.96	0.85	0.95	0.77	

Abbreviations: BCR, benefit to cost ratio; UDP, urea deep placement; VCR, value to cost ratio.

The significant interaction between treatment and marshland on yield in 2016B is shown in Table 4. In all cases, the UDP package was significantly better than urea broadcast, and both fertilized treatments were better than the control. The interaction is a result of the differences in the magnitude of yield increases brought about by either UDP and broadcast urea. Specifically, Cyabayaga, Cyaruhogo, Muvumba, and Rugeramigozi marshlands showed a lesser increase to UDP versus broadcast urea (from 0.68 to 0.86 mt ha^{-1}), whereas in the remaining marshlands yields increased from 1.20 to 1.39 mt ha^{-1}.

3.2 | Effect of UDP package on straw biomass and grain yield

The UDP package treatment increased rice straw biomass and grain yield compared to broadcasting urea (Tables 2 and 3). Both treatment and marshland were highly significant for both biomass and grain yield in both seasons ($p < 0.0001$). The only significant interaction between treatment and marshland was for grain yield in the 2016B season. On average, paddy rice yields in the UDP package treatment increased by 0.97 mt ha^{-1} and straw biomass by 0.86 mt ha^{-1} when compared to broadcasting urea. Highest average yields were obtained in the Bugarama marshland and lowest yields in Rugeramigozi, which reflects their relative fertility status (Table 1).

3.3 | Economic analysis

The UDP package resulted in greater VCRs and BCRs across all marshlands compared to the broadcast urea treatment (Table 5). While the average VCR across marshlands was only 1.84 and 1.98 for the 2016B and 2017A seasons for the current treatment involving broadcast urea, this increased to 3.25 and 3.16, well above the level of 2 considered necessary for technology adoption. Both treatment and marshland were highly significant in explaining yield variations for both VCR and BCR, but the interaction between marshland and treatment was not significant, indicating that response to treatments did not differ significantly between marshlands.

The net benefit of switching from the current fertilizer recommendation (200 kg of NPK 17-17-17 followed by a split application of 100 kg urea ha^{-1}) to the UDP package (a blend of DAP and KCl followed by a single application of 112.5 kg urea briquettes ha^{-1}) averaged US$332 and US$268 ha^{-1} for the two seasons. Marshland variation in net benefit was not significant for either season at $p < 0.05$, which indicates that benefits of changing fertilizer recommendations would be realized across marshlands. Of this net benefit, US$37 is derived from savings in fertilizer purchase and application costs.

3.4 | Sensitivity of the VCR to changes in labor costs

A sensitivity analysis to changes in labor costs (Table 6) shows that despite additional labor required for briquette application (15 person-days ha^{-1}) versus broadcast urea (6 person-days ha^{-1}), briquette application is still desirable (VCR > 2) in most marshlands even when labor costs increase by up to sixfold, or to $9.00 per person-day. The analysis also includes costs associated with processing the additional harvest. With the current labor cost being only $1.52 per person-day, it is not likely that the cost of labor would negatively impact on the profitability of the urea briquette fertilizer package in Rwanda, which includes DAP, KCl, and urea briquettes, should labor costs increase dramatically.

Although the net benefit to UDP versus broadcast urea would reduce should the current labor cost increase by almost eight times to $12 (Figure 2), the net benefit would still be

TABLE 3 Effects of urea treatment and marshland on number of tillers per plant, plant height, straw biomass, and paddy rice yield.

Province	Marshland	2016B Control	Current practice	UDP	Average	2017A Control	Current practice	UDP	Average
Number of tillers									
Western	Bugarama	12.2 b	15.1 ab	20.5 a	15.9 ab	10.3 c	14.8 b	18.7 a	14.6 bc
Eastern	Cyabayaga	11.3 c	16.5 b	19.9 a	15.9 ab	8.9 b	11.3 ab	13.7 a	11.3 d
Eastern	Cyaruhogo	11.0 c	16.0 b	18.4 a	15.1 ab	8.4 c	12.6 b	17.4 a	12.8 cd
Eastern	Cyunuzi	9.5 b	11.1 b	14.3 a	11.7 d	14.8 b	17.0 b	22.4 a	18.1 a
Eastern	Kanyonyomba	7.6 b	11.9 ab	12.2 a	10.6 d	9.6 b	12.2 ab	14.0 a	11.9 d
Southern	Mukunguri	12.3 b	17.0 b	23.3 a	17.6 a	8.4 a	11.6 a	13.9 a	11.3 d
Eastern	Muvumba	10.1 b	13.3 ab	14.5 a	12.7 cd	11.8 c	14.6 b	19.6 a	15.3 b
Southern	Rugeramigozi	12.4 c	15.2 b	19.8 a	15.8 ab	10.5 b	14.9 a	17.9 a	14.4 bc
Southern	Rwasave	11.6 c	14.0 bc	19.6 a	15.1 bc	10.8 c	15.8 b	18.6 a	15.0 bc
Plant height (cm)									
Western	Bugarama	101.0 b	116.0 a	118.0 a	111.7 a	101.0 b	116.0 a	120.0 a	112.1 ab
Eastern	Cyabayaga	103.0 c	115.0 ab	118.0 a	111.8 a	101.0 b	112.0 a	116.0 a	109.5 bcd
Eastern	Cyaruhogo	95.4 b	113.4 a	121.0 a	109.9 ab	98.2 b	117.2 a	125.0 a	113.5 ab
Eastern	Cyunuzi	95.6 b	104.3 ab	111.9 a	103.9 bc	102.0 b	113.0 ab	119.0 a	111.5 abc
Eastern	Kanyonyomba	100.0 b	107.0 ab	111.0 a	106.4 ab	95.9 b	103.1 ab	106.9 a	102.0 d
Southern	Mukunguri	99.3 c	114.2 ab	121.2 a	111.6 a	104.0 ab	113.0 a	136.0 a	117.9 a
Eastern	Muvumba	104.0 c	113.0 b	121.0 a	112.5 a	78.4 c	95.1 ab	103.8 a	92.4 e
Southern	Rugeramigozi	87.1 c	99.1 b	105.4 a	97.2 c	98.1 b	105.3 ab	109.2 a	104.2 cd
Southern	Rwasave	99.3 b	108.7 a	112.5 a	106.8 ab	93.3 c	105.9 b	114.3 a	104.5 cd
Above-ground biomass (straw, mt ha^{-1})									
Western	Bugarama	4.1 c	5.7 b	6.8 a	5.5 ab	6.3 c	7.4 ab	8.0 a	7.2 a
Eastern	Cyabayaga	4.0 c	5.9 ab	6.6 a	5.5 ab	3.8 c	5.2 b	6.2 a	5.0 e
Eastern	Cyaruhogo	3.3 c	4.9 b	5.9 a	4.8 b	4.7 c	6.6 ab	7.3 a	6.2 bc
Eastern	Cyunuzi	4.2 c	6.2 ab	6.9 a	5.8 a	4.2 c	6.2 ab	7.1 a	5.8 cd
Eastern	Kanyonyomba	3.9 c	5.5 b	6.5 a	5.3 ab	4.3 c	6.0 b	7.1 a	5.8 cd
Southern	Mukunguri	4.6 b	6.5 a	7.3 a	6.1 a	4.8 b	6.7 a	7.5 a	6.3 ab
Eastern	Muvumba	4.3 c	5.8 b	6.7 a	5.6 ab	4.1 c	5.7 b	6.8 a	5.5 b
Southern	Rugeramigozi	3.7 b	5.6 a	6.4 a	5.2 ab	3.9 b	5.8 a	6.6 a	5.4 de
Southern	Rwasave	4.1 b	6.1 a	6.8 a	5.7 ab	4.2 b	6.1 a	6.8 a	5.7 d
Rice (paddy) yield (mt ha^{-1})									
Western	Bugarama	NA	NA	NA	NA	4.4 c	7.1 ab	7.9 a	6.5 a
Eastern	Cyabayaga	NA	NA	NA	NA	2.7 c	4.8 b	5.6 a	4.4 c
Eastern	Cyaruhogo	NA	NA	NA	NA	3.2 c	5.3 b	6.2 a	4.9 b
Eastern	Cyunuzi	NA	NA	NA	NA	3.3 c	5.4 b	6.6 a	5.1 b
Eastern	Kanyonyomba	NA	NA	NA	NA	3.1 c	5.1 b	6.2 a	4.8 bc
Southern	Mukunguri	NA	NA	NA	NA	2.2 b	3.7 a	4.2 a	3.4 d
Eastern	Muvumba	NA	NA	NA	NA	3.1 c	5.1 b	6.3 a	4.9 bc
Southern	Rugeramigozi	NA	NA	NA	NA	2.2 b	4.2 a	4.8 a	3.8 d
Southern	Rwasave	NA	NA	NA	NA	2.8 b	5.0 a	5.4 a	4.4 c

Note: Means followed by the same letter are not significantly different at $p < 0.05$. Mean rice paddy yields for 2016B are in Table 4.

Abbreviations: NA, not applicable; UDP, urea deep placement.

TABLE 4 Significant marshland × treatment interaction on yield in 2016B.

		Treatments		
Province	Marshland	Control	Current practice	UDP
Western	Bugarama	3.2 l[†]	5.4 efg	6.7 ab
Eastern	Cyabayaga	3.3 kl	5.4 ef	6.2 bcd
Eastern	Cyaruhogo	2.6 m	4.8 gh	5.7 de
Eastern	Cyunuzi	3.0 lm	4.6 hi	5.8 cde
Eastern	Kanyonyomba	3.3 l	5.7 de	6.9 a
Southern	Mukunguri	3.0 lm	5.3 efg	6.7 ab
Eastern	Muvumba	3.9 jk	5.4 ef	6.3 bc
Southern	Rugeramigozi	2.8 lm	4.1 ij	4.8 gh
Southern	Rwasave	3.3 kl	4.9 fgh	6.3 bc

Note: Means followed by the same letter are not significantly different at $p < 0.05$.
Abbreviation: UDP, urea deep placement.

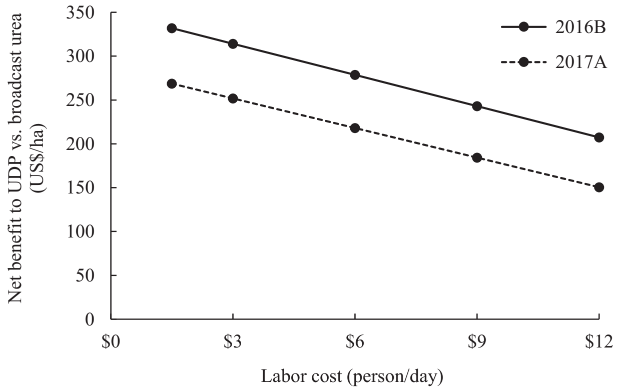

FIGURE 2 Net benefit to urea deep placement (UDP) versus broadcast urea against changes in labor cost.

substantial, and would have averaged US$207 and US$151 for the 2016B and 2017A seasons.

4 | DISCUSSION

Marked increases in number of tillers, plant height, aboveground biomass, and grain yield due to the UDP package were realized despite a 19% reduction in N application rate (or 15 kg ha^{-1}) in the UDP treatment package (65 vs. 80 kg ha^{-1} in the urea broadcast treatment). These findings concur with previous published reports of UDP improving plant height (Azam et al., 2012; Mizan, 2010; Naznin et al., 2013), number of tillers per plant (Bandaogo et al., 2014; Gaudin, 1988; Kabir et al., 2009; Miah & Masum, 2004), straw and grain yield (Bandaogo et al., 2014; Bowen et al., 2004; Jena et al., 2003; Savant & Stangel, 1990). While N use efficiency could not be quantified due to the absence of a treatment that contains P and K but not N, a substantial yield gain of 0.97 mt ha^{-1} while reducing the N application by 15 kg ha^{-1} necessarily implies a marked increase in N use efficiency with UDP. Increases in N use efficiency due to UDP have been reported in several countries (Bandaogo et al., 2014; Rochette et al., 2013; Yao et al., 2017; Zhang et al., 2017). More efficient N uptake translates to several environmental benefits, including lower levels of ammonium and nitrate in runoff and/or groundwater, decreased eutrophication, decreased emissions of nitrous oxides and ammonia, and subsequent mitigation of their GHG effects (Linquist et al., 2012).

The fact that grain yield was improved by UDP presents an opportunity to improve the import/export gap through reduced fertilizer use. Rice straw in Rwanda is valued as a livestock fodder and as mulch in banana, coffee, tomato, and other high value commodities. Additionally, rice straw is sold to companies manufacturing construction materials from straw (FONERWA, 2021).

The economic benefits of the UDP package treatment versus the current broadcast fertilizer recommendation are profound. The profitability of UDP was also reported by IFDC (2007) and Alam et al. (2013). The US$304 ha^{-1} average increase in net benefits is substantial for individual farmers. On a national level, given the 16,389 ha (2016B) and 16,922 ha (2017A) rice hectarage currently under fertilization (NISR, 2018), a national benefit of US$10.1 million annually (two seasons) would be realized by Rwanda rice farmers by switching to the UDP-based recommendation. Further, one could anticipate increased rice production of an average of some 32,000 mt paddy rice annually. These numbers are estimates from the data only and may be more or less these values based on actual distribution of rice production areas. Given that area for rice production has not increased in over a decade due to land availability (NISR, 2021), the only means to increase production is to achieve greater yields per ha. It is noteworthy to mention that adoption of UDP is technically feasible in Rwanda because rice growers traditionally transplant in squares of 20 × 20 cm, a practice which makes it

TABLE 5 Value to cost ratio (VCR), benefit to cost ratio (BCR), and net returns to UDP package versus broadcast urea treatment in seasons 2016B and 2017A.

Province	Marshland	2016B Current practice	2016B UDP	2017A Current practice	2017A UDP
VCR					
Western	Bugarama	2.0 b	3.7 a	2.5 b	3.7 a
Eastern	Cyabayaga	2.0 b	3.1 a	2.0 b	3.1 a
Eastern	Cyaruhogo	2.1 b	3.3 a	2.0 b	3.2 a
Eastern	Cyunuzi	1.5 b	3.0 a	1.9 b	3.5 a
Eastern	Kanyonyomba	2.3 b	3.9 a	1.9 b	3.3 a
Southern	Mukunguri	2.2 b	4.0 a	1.4	2.2 ($p = 0.056$)
Eastern	Muvumba	1.5 b	2.6 a	1.9 b	3.5 a
Southern	Rugeramigozi	1.2 b	2.1 a	1.9 b	2.8 a
Southern	Rwasave	1.5 b	3.2 a	2.1	2.8 ($p = 0.064$)
BCR					
Western	Bugarama	4.1 b	6.2 a	5.8 b	7.6 a
Eastern	Cyabayaga	4.2 b	5.8 a	3.6 b	5.1 a
Eastern	Cyaruhogo	3.6 b	5.2 a	4.1 b	5.8 a
Eastern	Cyunuzi	3.4 b	5.3 a	4.2 b	6.1 a
Eastern	Kanyonyomba	4.4 b	6.5 a	3.9 b	5.7 a
Southern	Mukunguri	4.1 b	6.2 a	2.5 b	3.7 a
Eastern	Muvumba	4.2 b	5.9 a	3.9 b	5.9 a
Southern	Rugeramigozi	3.0 b	4.3 a	3.0 b	4.3 a
Southern	Rwasave	3.7 b	5.8 a	3.8 b	4.9 a
Net benefit of UDP versus broadcast urea (US$ ha^{-1})					
Western	Bugarama		396.0		250.0
Eastern	Cyabayaga		265.0		269.0
Eastern	Cyaruhogo		275.0		284.0
Eastern	Cyunuzi		369.0		366.0
Eastern	Kanyonyomba		380.0		327.0
Southern	Mukunguri		401.0		198.0
Eastern	Muvumba		367.0		371.0
Southern	Rugeramigozi		226.0		213.0
Southern	Rwasave		421.0		148.0
p value			0.0533		0.1383

Note: Means followed by the same letter are not significantly different at $p < 0.05$.
Abbreviation: UDP, urea deep placement.

easier to drive down briquettes into soils than when rice is transplanted without distinct rows. Therefore, investment in additional labor for transplanting and in training of farmers in square transplanting is not needed.

Values of VCR and BCR for the UDP package are above thresholds indicated by Kihara et al. (2015) and CIMMYT (1988) for technology adoption. A sensitivity analysis indicated that given eight-fold increase in current labor costs, the UDP fertilizer package would still be more profitable than the current recommendation and result in VCRs for fertilizer application greater than 2. In our study, we did not measure costs associated with weeding. However, UDP has previously shown to reduce weeding labor by some 40% or 13 person-days when compared to broadcast urea, which is generally sufficient to offset the additional labor for briquette application (Thompson & Sanabria, 2010). The reduction in weeding costs is due to limited access to N due to its deep placement during weed establishment and to the faster rice canopy closure with UDP, which deprives weeds of sunlight.

The net benefits from UDP are sustainable compared to the current broadcast fertilizer recommendation irrespective of increment in labor cost with time. However, an unlikely negative scenario would occur if the labor cost increased, and the price of rice dramatically reduced implying a higher cost

TABLE 6 Value to cost ratios (VCRs) for fertilizer treatments as affected by labor costs for the nine study marshlands (averaged for two seasons).

Marshland	Labor cost ($US person-day^{-1})									
	$1.50		$3.00		$6.00		$9.00		$12.00	
	VCR gran. urea	VCR urea briquettes	VCR gran. urea	VCR urea briquettes	VCR gran. urea	VCR urea briquettes	VCR gran. urea	VCR urea briquettes	VCR gran. urea	VCR urea briquettes
Bugarama	2.3	3.7	2.2	3.4	2.1	2.9	1.9	2.5	1.8	2.2
Cyabayaga	2.0	3.1	1.9	2.9	1.8	2.5	1.7	2.1	1.6	1.9
Cyaruhogo	2.0	3.3	2.0	3.0	1.8	2.6	1.7	2.2	1.7	2.0
Cyunuzi	1.7	3.3	1.7	3.0	1.6	2.5	1.5	2.2	1.4	2.0
Kanyonyomba	2.1	3.6	2.0	3.3	1.9	2.8	1.8	2.5	1.7	2.2
Mukunguri	1.8	3.1	1.7	2.8	1.6	2.4	1.6	2.1	1.5	1.9
Muvumba	1.7	3.0	1.6	2.8	1.5	2.4	1.4	2.1	1.4	1.8
Rugeramigozi	1.5	2.5	1.5	2.3	1.4	1.9	1.3	1.7	1.2	1.5
Rwasave	1.8	3.0	1.7	2.7	1.6	2.3	1.5	2.0	1.4	1.8

of production compared to value of production. Adoption of UDP practice is expected to trigger large-scale production of briquettes by the private sector compared to small-scale production by farmer cooperatives. If this happens, the cost of production of briquettes would probably decrease, and hence make UDP practice more profitable than illustrated by our economic analyses.

5 | CONCLUSIONS

Replacing the current practice of applying fertilizers in lowland rice in Rwanda was studied. This practice consists of basal fertilizer application of 17-17-17 and broadcast urea at a rate of 200 and 100 kg, respectively, ha^{-1}. The proposed practice consists of basal application of DAP and KCl and deep application of urea briquettes at a rate of 73.9, 56.7, and 112.5 kg, respectively, ha^{-1}. The proposed practice is termed "UDP fertilizer package." From this study, UDP fertilizer package increases straw and grain yield of rice through increasing the number of tillers, and growth of plants (height), implying improved and sustained supply of nutrients to rice plants throughout the season, especially nitrogen, thanks to its slow release from deep-placed briquettes. UDP fertilizer package reduces N fertilizer application by 15 kg ha^{-1} and further reduces the cost of basal fertilizer application by substituting lower combined fertilizer rates of DAP and KCl for the current application of 17-17-17. Given an eight-fold increase in current labor costs, UDP fertilizer package would still be more profitable than the current practice and result in VCRs for fertilizer application greater than 2. Furthermore, the net benefits to UDP fertilizer package versus broadcast urea remain attractive enough even at eight times increase in current labor cost.

The research has particular relevance where NPK compounds such as 17-17-17 are being employed with broadcast urea in lowland rice systems. Compounds are generally more expensive than their constituent ingredients, as the manufacture of compounds requires stabilizers (usually lime) and manufacturing steps to granulate the constituent ingredients (urea and/or ammonium nitrate, DAP and KCl, or similar combinations). By using a DAP/KCl blend which is stable, and using urea briquettes for more efficient N utilization, both the volume and price of the fertilizer package was markedly reduced while yields were improved. Adoption of UDP fertilizer package will therefore lead to reduced investment in mineral fertilizers by smallholder farmers with increased benefits in yields and returns on investment in fertilizers. Moreover, the reduced use of mineral fertilizers and their increased use efficiency will reduce environmental pollution due to nutrients released from paddy rice fields to adjacent ecosystems.

Adoption of UDP requires investment in machines that make briquettes. Currently, the briquettes are produced in Rwanda using small-scale briquette machines purchased by a few rice cooperatives. The machines are not robust and operate for only a few weeks every year. A more efficient model would be to produce urea briquettes centrally using higher capacity and more robust briquette machines and distribute already briquetted urea to rice cooperatives. While many cooperatives have already been exposed to briquettes, some training would be required to initiate all rice farmers to briquette application. The basal blend of DAP and MOP used in this study can be produced in Rwanda or can be imported from any of several East Africa blending facilities.

AUTHOR CONTRIBUTIONS

John Kayumba: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing. **John Wendt**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—review and editing. **Athanase Rusanganwa Cyamweshi**: Project administration; resources; supervision; writing—review and editing. **Pierre Celestin Ndayisaba**: Writing—review and editing. **Shem Kuyah**: Writing—review and editing. **Mercy Ngunjiri**: Methodology; visualization. **Jules Rutebuka**: Writing—review and editing. **Nsharwasi Leon Nabahungu**: Formal analysis; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Alam, M. M., Karim, M. R., & Ladha, J. K. (2013). Integrating best management practice for rice with farmers' crop management techniques: A potential option for minimizing rice yield gap. *Field Crops Research*, *144*, 62–68. https://doi.org/10.1016/j.fcr.2013.01.010

Alimi, T., & Manyong, V. (2000). *Partial budget analysis for on-farm research. IITA research guide*. International Institue Tropical Agriculture.

Azam, M. T., Ali, M. H., Karim, M. F., Rahman, A., Jalal, M. J., & Mamun, A. F. M. (2012). Growth and yield of boro rice as affected by different urea fertilizer application method. *International Journal of Sustainable Agriculture*, *4*, 45–51.

Bandaogo, A., Bidjokazo, F., Youl, S., Safo, E., Abaidoo, R., & Andrews, O. (2014). Effect of fertilizer deep placement with urea supergranule on nitrogen use efficiency of irrigated rice in Sourou Valley (Burkina Faso). *Nutrient Cycling in Agroecosystems*, *102*(1), 79–89. https://doi.org/10.1007/s10705-014-9653-6

Bangladesh Rice Research Institute (BRRI). (2021). *Annual report of soil and fertilizer management programme*. BRRI.

Bowen, W. T., Diamond, R. B., Singh, U., & Thompson, T. P. (2004). Urea deep placement increases yield and save nitrogen fertilizer in farmer's field in Bangladesh. Rice is life: Scientific perspectives for the 21st century. *The world rice research conference*, *4–7 November*, *Tsukuba, Japan* (pp. 369–372).

Cassman, K. G., Peng, S., Olk, D. C., Ladha, J. K., Reichardt, W., Dobermann, A., & Singh, U. (1998). Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Research*, *56*, 7–39.

Chen, Z., Wang, Q., Ma, J., Zou, P., & 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. https://doi.org/10.1038/s41598-020-67110-6

CIMMYT. (1988). *From agronomic data to farmer recommendations: An economics workbook*. CIMMYT Mexico.

FONERWA. (2021). *Investing in sustainable construction materials: Zero carbon affordable housing for Rwanda*. http://www.fonerwa.org/sites/default/files/2021-06/Rwanda_Green_Fund_Factsheet_Investing_in_Sustainable_Construction_Materials.pdf

Gaihre, Y. K., Singh, U., Islam, S. M. M., Huda, A., Islam, M. R., Satter, M. A., Sanabria, J., Islam, M. R., & Shah, A. L. (2015). Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. *Geoderma*, *259-260*, 370–379. https://doi.org/10.1016/j.geoderma.2015.06.001

Gaudin, R. (1988). L'ammoniac NH3, une cleť pour comprendre l'efficaciteť des supergranules d'ureťe en riziculture irrigueťe. *L'Agronomie Tropicale*, *43*, 30–36.

Global Rice Science Partnership. (2013). *Rice Almanac. IRRI, Los Baños, Philippines (Fourth)*. International Rice Research Institute. https://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Rice+Almanac#1

Guo, Y., & Wang, J. (2021). Poverty alleviation through labor transfer in rural China: Evidence from Hualong County. *Habitat International*, *116*, 102402. https://doi.org/10.1016/j.habitatint.2021.102402

Hasanuzzaman, M., Fujita, M., Islam, M. N., Ahamed, K. U., & Nahar, K. (2009). Performance of four irrigated rice varieties under different levels of salinity stress. *International Journal of Integrative Biology*, *6*, 85–90.

International Fertilizer Development Center (IFDC). (2007). *Bangladesh will dramatically expand technology that doubles efficiency of urea fertilizer use. IFDC Report*. IFDC. https://dataverse.ifdc.org/dataset.xhtml?persistentId=hdl:20.500.13038/FK2/OJOVQH

International Food Policy Research Institute (IFPRI). (2004). *Annual report, 2003-2004*. IFPRI.

Jena, D., Misra, C., & Bandyopadhyay, K. K. (2003). Effect of prilled urea and urea super granules on dynamics of ammonia volatilization and N use efficiency of rice. *Indian Journal of Soil Science*, *51*, 257–261.

Kabir, M. H. W., Quddus, K. G., Alli, M. Y., & Hossain, S. M. I. (2009). Effect of urea super granule deep placement on rice cultivation in the tidal coastal area of Khulna region, Khulna. *Journal of Bangladesh Agricultural University*, *7*, 1027–1032.

Kelly, V., & Murekezi, A. (2000). *Fertilizer response and profitability in Rwanda: A synthesis of findings from MINAGRI studies conducted by The Food Security Research Project (FSRP) and The FAO Soil Fertility Initiative*. Michigan State University, Department of Agricultural, Food, and Resource Economics, Food Security Collaborative Working Papers.

Kihara, J., Huising, J., Nziguheba, G., Waswa, B., Njoroge, S., Kabambe, V., Iwuafor, E., Kibunja, C., Esilaba, A., & Coulibaly, A. (2015). Maize response to macronutrients and potential for profitability in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems*, *105*, 171–181. https://doi.org/10.1007/s10705-015-9717-2

Linquist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., & van Groenigen, K. J. (2012). Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, *135*, 10–21. https://doi.org/10.1016/j.fcr.2012.06.007

Miah, A. K., & Masum, S. M. (2004). Application of different forms of urea for rice. *Indian Journal of the Society of Soil Science*, *44*, 267–270.

Miah, M., Gaihre, Y., Hunter, G., Singh, U., & Hossain, S. (2016). Fertilizer deep placement increases rice production: Evidence from farmers' fields in Southern Bangladesh. *Agronomy Journal*, *108*, 805–812. https://doi.org/10.2134/agronj2015.0170

Mizan, R. (2010). *Effect of nitrogen and plant spacing on the yield of boro rice cv. BRRI dhan 45* [Master's thesis, Department of Agronomy, Bangladesh Agricultural University].

Nabahungu, L., Cyamweshi, A. R., Kayumba, J., Kokou, K., Mukuralinda, A., Cirhuza, J. M., & Wortmann, C. S. (2020). Lowland rice yield and profit response to fertilizer application in Rwanda. *Agronomy Journal*, *112*, 1423–1432. https://doi.org/10.1002/agj2.20006

Nabahungu, N. L., & Visser, S. M. (2011). Farmers' knowledge and perception of agricultural wetland management in Rwanda. *Land Degradation and Development*, *24*, 363–374. https://doi.org/10.1002/ldr.1133

National Institute of Statistics of Rwanda (NISR). (2018). *2017 Seasonal agricultural survey*. https://www.statistics.gov.rw/publication/seasonal-agricultural-survey-report-2017

National Institute of Statistics of Rwanda (NISR). (2021). *Seasonal agricultural survey annual report*. https://www.statistics.gov.rw/datasource/seasonal-agricultural-survey-2021

Naznin, A., Afroz, H., Hoque, S., & Mian, H. (2013). Effects of PU, USG and NPK briquette on nitrogen use efficiency and yield of BR22 rice under reduced water condition. *Journal of the Bangladesh Agricultural University*, *11*, 215–220.

Peng, S., Buresh, R. J., Huang, J., Yang, J., Zou, Y., Zhong, X., Wang, G., & Zhang, F. (2006). Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crops Research*, *96*(1), 37–47. https://doi.org/10.1016/j.fcr.2005.05.004

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rochette, P., Angers, D. A., Chantigny, M. H., Gasser, M. O., MacDonald, J. D., Pelster, D. E., & Bertrand, N. (2013). Ammonia volatilization and nitrogen retention: How deep to incorporate urea? *Journal of Environmental Quality*, *42*, 1635–1642. https://doi.org/10.2134/jeq2013.05.0192

Roger, P. A., Kulasooriya, S. A., Tirol, A. C., & Crasswell, E. T. (1980). Deep placement: A method of nitrogen fertilizer application compatible with algal nitrogen fixation in wetland rice soils. *Plant and Soil*, *57*(1), 137–142.

Savant, N. K., & Stangel, P. J. (1990). Deep placement of urea supergranules in transplanted rice: Principles and practices. *Fertilizer Research*, *25*, 1–83.

Thompson, T. P., & Sanabria, J. (2010). *The division of labor and agricultural innovation in Bangladesh: Dimensions of gender*. International Fertilizer Development Center. https://hdl.handle.net/20.500.13038/FK2/KID3DH/UMBUQD

Verdoodt, A., & Van Ranst, E. (2003). *Land evaluation for agricultural production in the tropics - A large-scale land suitability classification for Rwanda*. Laboratory of Soil Science, Ghent University.

Wada, G., Shoji, S., & Mae, T. (1986). Relationship between nitrogen absorption and growth and yield of rice plants. *JARQ*, *20*, 135–145.

Yao, Y., Zhang, M., Tian, Y., Zhao, M., Zhang, B., Zhao, M., Zeng, K., & Yin, B. (2017). Urea deep placement for minimizing NH_3 loss in an intensive rice cropping system. *Field Crops Research*, *218*, 254–266. https://doi.org/10.1016/j.fcr.2017.03.013

Zhang, M., Yao, Y., Zhao, M., Zhang, B., Tian, Y., Yin, B., & Zhu, Z. (2017). Integration of urea deep placement and organic addition for improving yield and soil properties and decreasing N loss in paddy field. *Agriculture, Ecosystems and Environment*, *247*, 236–245. https://doi.org/10.1016/j.agee.2017.07.001

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