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On-farm evaluation of fertilizer recommendation methods: Impacts on rice yield and economic benefits in subtropical soils

Md. Enamul Haque[1] ✉
Richard W. Bell[2]
Miaomiao Cheng[3]
Md. Abdus Satter[4]
Md. Baktear Hossain[5]
Md. Jahiruddin[6]
Md. Mofizur Rahman Jahangir[7]
Md. Aminul Islam[8]
Sohela Akhter[9]
Md. Monayem Miah[10]
A. K. M. Anisur Rahman[11]


(✉ Corresponding Author)

[1,2,3]*School of Agricultural Science, Murdoch University, Murdoch 6150, Australia.*
[1]*Email:* Enamul.haque71@gmail.com
[2]*Email:* R.Bell@Murdoch.edu.au
[3]*Email:* Miaomiao.Cheng@dpird.wa.gov.au
[4,5]*Bangladesh Agricultural Research Council, Farmgate, Dhaka, Bangladesh.*
[4]*Email:* A.Satter1959@gmail.com
[5]*Email:* Baktear@gmail.com
[6,7]*Department of Soil Science, Bangladesh Agricultural University, Mymensingh, Bangladesh.*
[6]*Email:* M_jahiruddin@yahoo.com
[7]*Email:* Mmrjahangir@bau.edu.bd
[8]*Soil Science Division, Bangladesh Rice Research Institute, Gazipur, Bangladesh.*
[8]*Email:* Aminbrri@gmail.com
[9]*Soil Science Division, Bangladesh Agricultural Research Institute, Gazipur, Bangladesh.*
[9]*Email:* Sohela_akhter@yahoo.com
[10]*Agricultural Economics Division, Bangladesh Agricultural Research Institute, Gazipur, Bangladesh.*
[10]*Email:* Monayem09@yahoo.com
[11]*Department of Medicine, Bangladesh Agricultural University, Mymensingh, Bangladesh.*
[11]*Email:* Arahman_med@bau.edu.bd

Abstract

Bangladesh publishes fertilizer recommendations but most farmers do not use these recommendations. In this study, we tested the performance of the Fertilizer Recommendation Guide (FRG), Rice Crop Manager (RCM) and Soil Testing Kit (STK) for determining fertilizer requirements of monsoon rice (Oryza sativa L) against Farmers' Fertilizer Practice (FFP). Rates of nitrogen, phosphorus, potassium, sulfur and zinc were determined by four methods and used on 72 farmer's fields in five agro-ecological zones (AEZ) over two years. All methods produced significantly higher grain yield than FFP (4.12 t ha-1): they were 13.8%, 9.6% and 8.3% higher for STK, RCM and FRG, respectively. RCM didn't perform consistently across the locations. Overall, the STK performed the best followed by FRG. The superiority of STK is attributed to its assessment of current soil status while the FRG recommendation is grounded on an older data set of soil analysis for each AEZ. The N dose was comparable among the methods while P dose was much higher for FFP, and RCM underestimated the K requirement of rice. Farmers declined to adopt the STK. By contrast, the supply of FRG information to the farmers by providing a simplified card with training is a simple and accessible technology.

Keywords: Adoption, FRG card, Nitrogen, Phosphorus, Potassium, Rice Crop Manager, Soil Test Kit, Sulfur, Zinc.

Contents

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Contribution of this paper to the literature:
Tools have been developed to assist farmers in making better fertilizer decisions, but they are rarely tested against one another and demonstrated to be more effective than farmers' current fertilizer use. We demonstrated that an expert-driven fertilizer recommendation system was accessible to smallholder farmers and achieved an 8% average yield increase.

1. Introduction

Rice (Oryza sativa L.) is the most dominant crop in Asia while about 40% people of the world consume rice as a major staple food. Rice crops in Bangladesh occupy about 75% of the crop area and rice-based cropping system is predominant [1]. The rice soils are commonly deficient in N, P, K, S and Zn. In the intensive, high yield cropping systems of south Asia, especially in India and Bangladesh, farmers generally apply excessive P fertilizer to rice but generally insufficient K, S or Zn [2]. Nitrogen applications relative to recommendations vary with farm size, cropping pattern and crop species [2]. However, improvements in N use efficiency can increase crop yields [3] since commonly less than 50% of urea-N is taken up by the crops and the rest is lost through leaching (NO3), volatilization of NH3 [4] and denitrification (N2O, N2) processes [5] and thereby contaminating environment [6].

Optimising the use of fertilizers continues to be a global concern since crop yield loss occurs with underuse while the risk of environmental loss increases with overuse. There are numerous fertilizer recommendation systems for crop cultivations globally. According to Beneduzzi, et al. [7] a literature search identified 12 methods for recommending N, eight methods for P, and seven methods for recommending K, in addition to five computer programs to make fertilizer recommendations at varying rates. Buresh, et al. [8] determined fertilizer K and P requirements for rice (Oryza sativa L.) cultivation by the site-specific nutrient management (SSNM) approach using estimated target yield, nutrient balances, and yield gains from added nutrients. That approach was based on model estimates without reliance on fresh soil analysis [9]. Dobermann and Cassman [10] argued that effective strategies for site-specific nutrient management should be based on a quantitative understanding of the relationships between nutrient supply and crop demand.

Usually, soil analysis is considered as an essential step for evaluation of soil fertility and thus on the fertilizer recommendation. Soil tests provide a scientific basis for fertilizer recommendations. Understanding and measuring spatial variability regarding nutrient availability in the soil is crucial to defining site-specific fertilizer management strategies to increase production efficiency and sustainability of agricultural production [11]. However, soil chemical analysis is expensive and time consuming to the point of being economically unfeasible for site-specific nutrient application in low value-added crops [12]. For smallholder farms, spatial and temporal variability in nutrient status on many small fields adds to the cost of using soil testing for site specific nutrient management.

There are three methods of fertilizer recommendation now available in Bangladesh – FRG [13] Rice Crop Manager (RCM) and Soil Testing Kit (STK). However, the majority of farmers do not use those methods [2] and employ their own calculation which in this study we have called Farmers' Fertilizer Practice (FFP). The fertilizer rates proposed may vary among recommendation methods but their impact on crop yield and profitability is not known. With this understanding, we studied performances of three fertilizer recommendation methods relative to FFP, with two objectives: (i) to determine the fertilizer (urea, TSP, MoP, gypsum and zinc sulphate) requirement for transplanted aman rice, and (ii) to identify the best method of fertilizer recommendation for rice in terms of yield benefits, economic return and adoptability by smallholder farmers.

2. Materials and Methods

2.1. Experimental Site and Soil

The field trials were conducted in six locations representing five agro-ecological zones (AEZ) of the country. In each location, the experiment was set up in six sites representing six farmer plots and it was done in two years (2018 and 2019) giving a total of 72 field trials (6 locations × 6 sites × 2 years) (Figure 1).

All the experimental sites were on medium-high land. Bangladesh has a sub-tropical humid climate and is characterized by hot and humid summer and cool dry winter. The country experiences monsoon rainfall, 80% of which occurs between June and October when transplanted Aman rice is grown. General characteristics of the soils under the experiments are presented in Table 1. The methods for soil analysis were followed as outlined by Page, et al. [14].

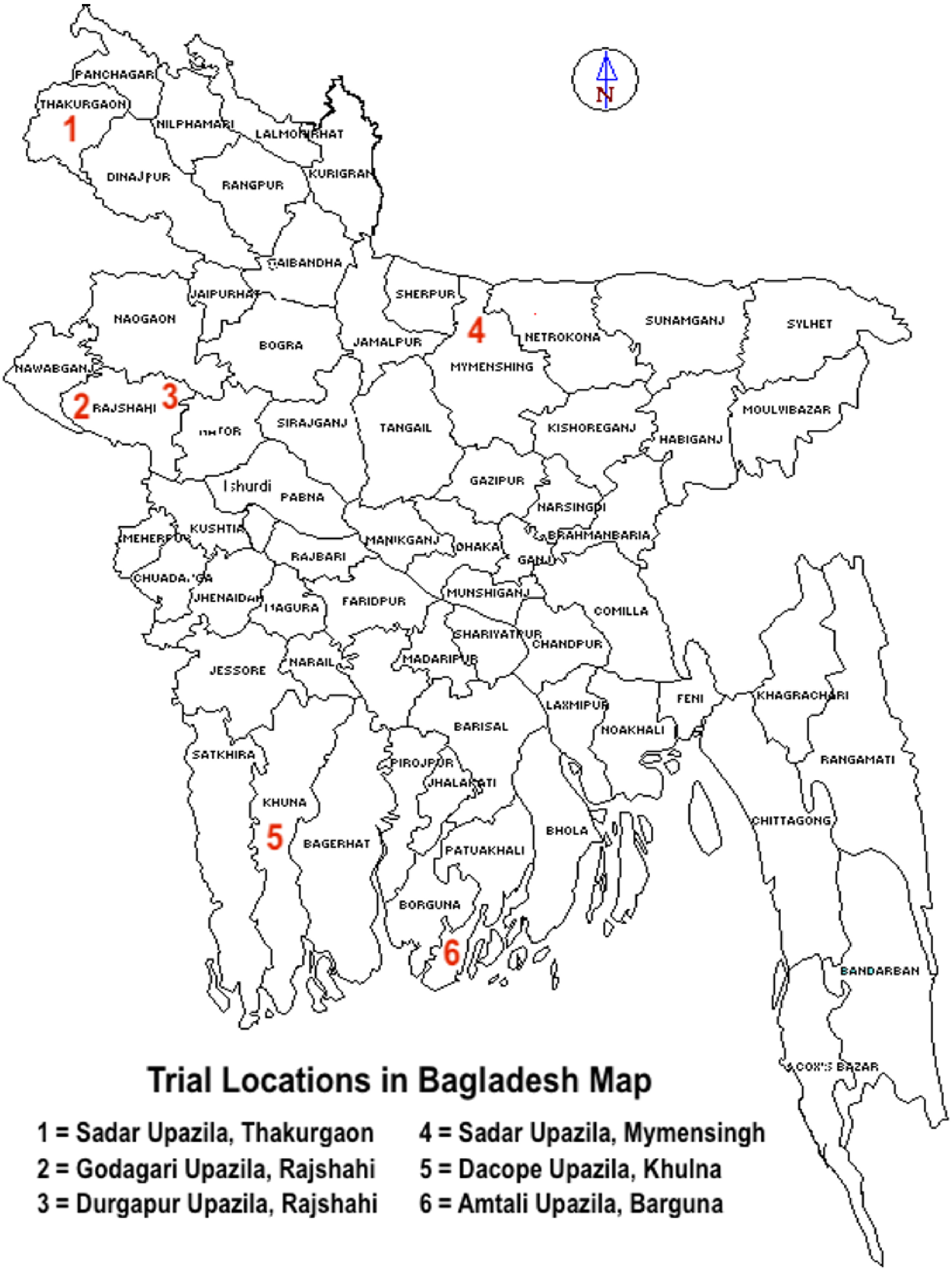

Figure 1. Map of Bangladesh showing trial locations.

Table 1. General characteristics of soils in different locations and sites under experiments.

Parameters	Durgapur	Godagari	Mymensingh Sadar	Thakurgaon Sadar	Dacope	Amtali	Methods
AEZ	11	26	9	1	13	13	GIS
Texture	Silt loam	Silty clay loam	Silt loam	Sandy clay loam	Silty clay	Silty clay	Hydrometer
pH	6.5-7.2	5.7-6.9	6.0-7.3	5.6-6.1	6.6-7.9	6.6-7.9	Soil-water ratio 1:2.5
Organic matter %	1.45-2.25	1.45-2.25	1.45-2.25	1.45-2.55	1.45-2.25	1.45-2.25	Wet oxidation
Total N (%)	0.045-0.085	0.045-0.085	0.045-0.085	0.045-0.085	0.045-0.085	0.045-0.085	Kjeldahl
Extractable P (mg /kg)	3.75-11.3	11.3-18.8	3.75-11.3	11.3-18.8	3.75-11.3	3.75-11.3	$NaHCO_3$ extraction
Exch. K ((cmol/kg)	0.085-0.225	0.085-0.225	0.045-0.085	0.045-0.085	0.085-0.225	0.085-0.225	NH4OAc extraction
Extractable S (mg /kg)	5.4-16.2	5.4-16.2	5.4-16.2	5.4-16.2	37.8-48.5	37.8-48.5	$CaCl_2$ extraction
Extractable Zn ((mg /kg)	0.27-0.81	0.27-0.81	0.81-1.36	0.27-0.81	1.36-1.89	1.36-1.89	DTPA extraction

Note: AEZ 1 = Old Himalayan piedmont plain, 9 = Old Brahmaputra floodplain, 11 = High Ganges River floodplain, 13 = Ganges tidal floodplain, 26 = High barind tract.
Source: FAO/UNDP [15].

Three types of fertilizer recommendation methods - FRG, RCM and STK, and FFP were tested in 72 farmers' (36 farmers each year) plots during two consecutive aman rice seasons of 2018 and 2019.

In Bangladesh, soil fertility experts have developed a Fertilizer Recommendation Guide (FRG) for all 30 AEZs for the farmers to select a recommended dose of fertilizers in their crops. Here fertilizer recommendation for a crop or cropping pattern is given on the basis of general fertility level of an AEZ. The Bangladesh Agricultural University (BAU), Mymensingh has developed a low-cost rapid soil testing technology i.e. Soil Testing Kit (STK) based on an on-site soil test, from which a fertilizer requirement for a crop is estimated. The Rice Crop manager (RCM) is a web-based fertilizer recommendation system developed by IRRI for site-specific nutrient management (SSNM) in the specific rice fields [8]. Before initiating crop establishment with RCM (http://webapps.irri.org/in/od/rcm), each farmer is interviewed to collect essential data inputs. The data collected includes: the farmer's field location, field size, rice variety, anticipated age of seedlings at transplanting, water management (irrigated or rainfed), rice yield in previous years with the same or similar variety, portion of above-ground residues from the previous crop retained in the field, and the farmer's choice of fertilizer sources. RCM utilizes this data to calculate a field-specific fertilizer recommendation tailored to achieve a target yield set by RCM. The RCM recommendation includes rates and timings for the application of fertilizer sources selected by the farmer [16].

2.2. Treatments and Design

Each method of fertilizer estimation is considered as a treatment. The experiment consisted of four treatments: T1 = Farmer fertilizer practice (FFP), T2 = FRG based fertilizer dose, T3 = RCM based fertilizer dose and T4 = STK based fertilizer dose. Urea (46% N), triple superphosphate (TSP 20% P), muriate of potash (MoP 50% K), gypsum (18% S) and zinc sulphate heptahydrate (21% Zn) were used to supply N, P, K, S, & Zn, respectively. The doses of nutrients based on the four methods including FFP are given in Table 2 and their fertilizer conversions are shown in supplementary Table S1. Each experiment was laid out in a randomized complete block design (RCBD) with six dispersed replications, i.e. each farmer/site represented one replication. So, there were 12 plots in each location for both years; farmers/sites were different for the two years. Each plot size ranged from 115 to 334 m2 (Table 3).

Table 2. Estimation of N, P, K, S and Zn rates based on four different methods for five locations for use in transplanted Aman rice crops (Average of 2 years).

Location (Upazila)	Fertilizer rate estimation methods	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Potassium (kg/ha)	Sulphur (kg/ha)	Zinc (kg/ha)
Durgapur, Rajshahi	FFP	93.8	26.1	39.5	5.2	1.89
	FRG	79.9	8.5	38.0	9.9	1.61
	STK	88.7	8.0	75.5	11.2	2.14
	RCM	95.4	10.3	24.0	5.1	1.56
	Mean ± SD	89.4 ± 7.0	13.2 ± 8.6	44.3 ± 22.0	7.9 ± 3.1	1.8±0.28
Godagari, Rajshahi	FFP	106.0	15.3	36.8	12.0	0.91
	FRG	88.9	10.7	62.5	8.5	0.49
	STK	88.7	3.0	53.0	13.4	4.25
	RCM	117.0	12.2	29.8	7.5	2.45
	Mean ± SD	100 ± 13.9	10.3 ± 5.2	45.5 ±14.9	10.3 ±2.8	2.03±1.71
Mymensingh, Sadar	FFP	50.0	12.6	29.5	0.5	0.00
	FRG	89.1	9.1	43.0	7.7	1.28
	STK	88.7	9.2	69.3	5.6	2.14
	RCM	139.3	24.6	33.8	3.4	1.31
	Mean ± SD	91.7 ±36.6	13.9 ± 7.3	43.9 ± 17.8	4.3 ±2.8	1.18±1.71
Thakurgaon, Sadar	FFP	99.2	18.9	48.3	14.1	3.15
	FRG	86.4	8.4	39.5	8.5	1.59
	STK	86.2	10.1	64.8	8.7	3.17
	RCM	70.2	9.7	35.8	6.3	2.38
	Mean ± SD	92.0 ±11.9	12.3 ± 4.8	45.1 ±12.9	7.9 ± 3.3	1.86±0.75
Dacope, Khulna	FFP	69.1	17.3	42.3	4.2	0.00
	FRG	81.7	12.7	34.3	4.3	1.28
	STK	88.9	11.0	44.5	6.8	2.64
	RCM	73.4	9.7	24.3	8.7	0.79
	Mean ± SD	85.5 ± 8.8	11.8 ±3.3	47.1 ± 9.2	9.4 ± 2.2	2.57 ± 1.1
Amtali, Barguna	FFP	84.4	20.1	12.0	3.0	0.00
	FRG	72.7	8.6	29.3	3.4	1.37
	STK	89.1	13.0	65.5	4.5	2.15
	RCM	84.4	9.0	24.0	1.2	0.88
	Mean ± SD	82.6 ± 7.0	12.7 ± 5.3	32.7 ± 23.0	3.0 ± 1.4	1.10±0.90

Note: FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM = Rice crop manager.

2.3. Crop Management

Rice (varieties mentioned in Table 3) was grown as a rainfed crop during July to November (kharif season) in each site and location. Thirty-day-old rice seedlings were transplanted at three seedlings per hill with a spacing of 20 × 20 cm. Urea was applied in three splits - 50% urea during final land preparation, 25% urea at 30 days (tiller stage) and 25% urea at 50 days after transplanting (panicle initiation stage). The other fertilizers viz. TSP, MoP, gypsum and zinc sulphate were added during final land preparation before transplanting rice seedlings. Pre and post emergence herbicides were used to all plots as per requirement. Insecticides 'Brifer 5 G' and 'Cidial 5 G' were used to control insect attack principally stem borer of rice. Irrigation was required in some sites before final land preparation. The crop was harvested at maturity from four randomly selected quadrats of $10m^2$ from each plot to record their yields. The yields were reported at 14% grain moisture.

2.4. Statistical Analysis

Yield data were statistically analyzed by MSTAT-C statistical software program (Michigan State University, USA) based on a randomized complete block design (RCBD) and the mean differences were compared by Duncan's Multiple Range Test (DMRT) [17]. Correlation statistics was done to examine the relationship between the methods of fertilizer estimation (FFP, FRG, RCM and STK) and pairwise treatment comparisons were done by Tukey's HSD (Honest Significant Difference) method. The impact of nutrients or fertilizers (N, P, K, S & Zn) on rice yield were evaluated by mixed-effects linear regression models [18].

2.5. Economic Analysis

Total variable costs were calculated considering costs for land preparation, seedlings, fertilizers, irrigation, harvesting, and labor for all operations including threshing and drying. Gross return was calculated by multiplying the amount of produce by its corresponding price at harvest. Gross margin was calculated by subtracting variable cost from gross return. Each of the treatments was evaluated based on total variable cost, gross return, gross margin and benefit-cost ratio. The labor required to complete each operation (land preparation, irrigation, and herbicide or insecticide application) in a particular treatment plot was recorded and converted to person-days /ha considering 8h as equivalent to one person-day and the daily labor wage was Tk. 400 (1US$ = 85 Tk.) per person per day (Bangladesh Government wage rate). Prices of urea, TSP, MOP, gypsum and zinc sulphate were 16, 22, 15, 10 and 180 Tk./kg; urea, TSP and MoP prices are government subsidized.

Table 3. Locations, rice varieties, seedling age, and transplanting and harvesting dates of crops during 2018 and 2019.

Year	Location	No. of field sites	GPS location		Individual plot size (m^2)	Rice varieties	Seedling age (days)	Seedling transplanting period	Harvesting date
			Latitude	Longitude					
2018	Durgapur, Rajshahi	6	24°27'27"N - 24°28'8"N	88°45'23"E - 88°45'54"E	264	BRRIdhan72	24-25	29-31 Jul 2018	9-17 Nov 2018
	Godagari, Rajshahi	6	24°23'46"N - 24°24'05"N	44°26'27"E - 44°26'57"E	238	BRRIdhan51	30-35	11-18 Jul 2018	9-17 Nov 2018
	Sadar, Mymensingh	6	24°40'53"N - 24°41'14"N	90°26'6"E - 90°27'0"E	213	BRRIdhan49	30-35	5-13 Aug 2018	22-27 Nov 2018
	Sadar, Thakurgaon	6	25°59'59"N - 26°0'0"N	88°28'27"E - 88°30'34"E	334	BRRIdhan51	25-30	30 Jul - 8 Aug 2018	13-19 Nov 2018
	Dacope, Khulna	6	22˚34'59"N - 22˚36'30"N	89˚28'2"E - 89˚30'81"E	214	BR-23	30-35	3-15 Sep 2018	12-24 Dec 2018
	Amtali, Barguna	6	22˚2'14"N –22˚2'26" N	90˚14'30"E- 90˚14'34" E	227	BR-23	30-35	9-16 Sep 2018	13-19 Dec 2018
2019	Durgapur, Rajshahi	6	24˚25'36"N - 24˚25'38"N	88˚44'38"E - 88˚44'39"E	119	BRRIdhan48	24-25	26-28 Aug 2019	16-Nov 2019
	Godagari, Rajshahi	6	24˚23'42"N - 24˚43'05"N	88˚26'27"E - 88˚26'47"E	179	BRRIdhan51	24-27	16-19 Jul 2019	16-18 Nov 2019
	Sadar, Mymensingh	6	24°40'56"N - 24°41'49"N	90°25'07"E - 90°26'49"E	115	BRRIdhan49	29-34	1-11 Aug 2019	12-26 Nov 2019
	Sadar, Thakurgaon	6	26°01'17"N - 26°03'36"N	88°28'49"E - 88°30'40"E	175	BRRIdhan51	22-35	4-28 Aug 2019	17-25 Nov 2019
	Dacope, Khulna	6	22°36'20"N - 22°36'38"N	89°18'36"E - 89°30'9"E	187	BR-23	30-40	30 Aug - 18 Sep 2019	8-22 Dec, 2019
	Amtali, Barguna	6	22°2'16"N –22°2'30" N	90°14'32"E-90°14'51" E	131	BR-23	28-30	7-19 Sep 2019	9-18 Dec 2019

3. Results

3.1. Variations in the Estimated Fertilizer Rates

The nutrient or fertilizer rates varied with different methods of estimation. The average N rate ranged from 83.1 to 96.6 kg/ha, with the highest estimation by RCM and the lowest by FRG, while for FFP and STK rates were 83.7 and 88.4 kg N/ha, respectively (Figure 2). For P, the FFP had the highest rate, 18.4 kg/ha, while STK recommended the lowest, 9.1 kg/ha. The STK estimated the highest rate of K (62.1 kg/ha) and RCM proposed the lowest (27.3 kg/ha). For S and Zn also, STK estimation was the highest followed by RCM. The Zn rate was <1 kg/ha for FFP. Hence, the FFP rate of P was double the value of STK while in case of K the FFP rate was half of the STK rate.

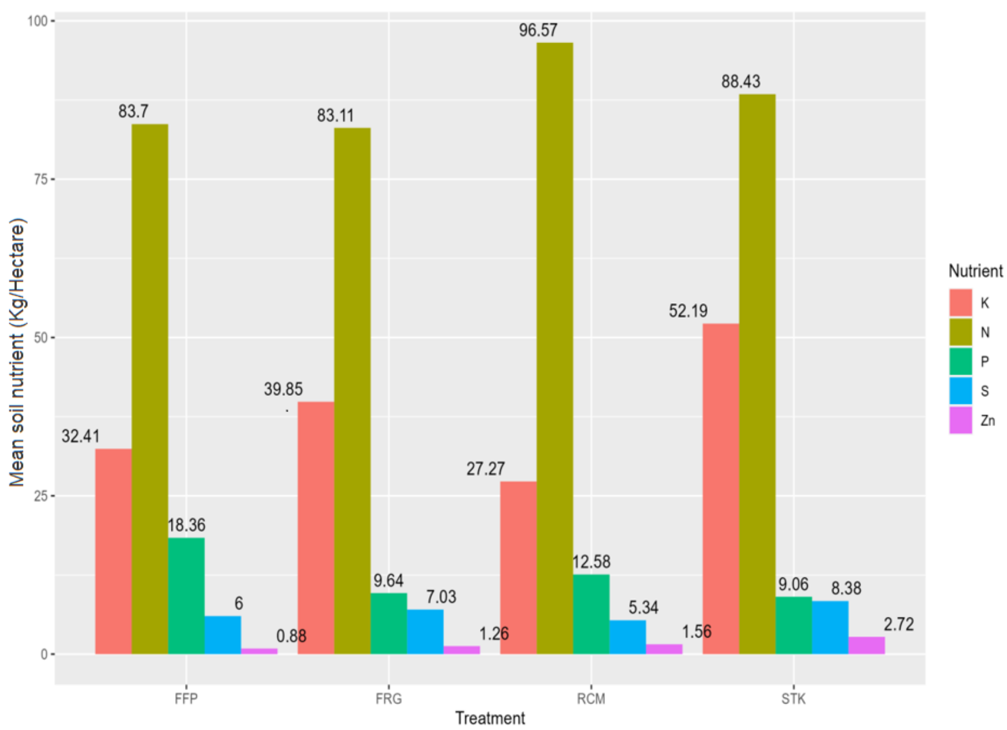

Figure 2. Nutrient rates (kg/ha) as estimated by different methods over the locations.

Note: FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, RCM=Rice crop manager, STK=Soil testing kit. RCM = Rice crop manager.

3.2. Grain Yield

The two years' average yields of rice against each fertilizer assessment method for each location and sites are presented in Figure 3. The year-wise grain yield for 2018 and 2019 are shown in Table S2 (Supplementary).

The grain yield varied with different fertilizer recommendation methods, locations and sites. The STK method always gave the highest grain yield and FFP gave the lowest. Overall, RCM and FRG methods produced an identical effect on rice yield. The result trends were STK > RCM = FRG > FFP.

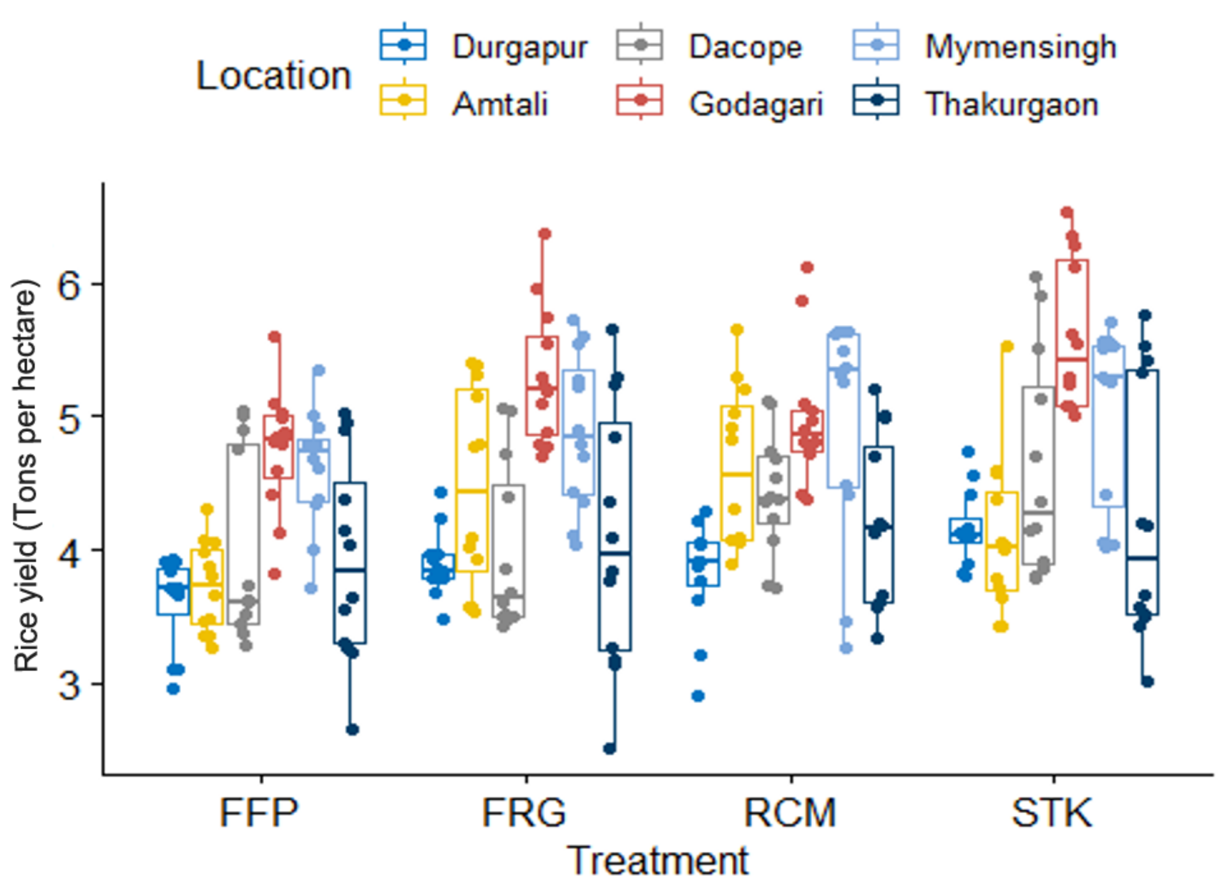

Figure 3. Effects of different methods of fertilizer estimation on rice yield at different locations.

Note: FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, RCM = Rice crop manager, STK=Soil testing kit

Considering location variations, the grain yield recorded at Durgapur (Rajshahi district) varied from 3.96 to 4.58 t/ha, Godagari (Rajshahi) from 5.23 to 6.16 t/ha, Mymensingh Sadar from 5.07 to 5.52 t/ha, Thakurgaon Sadar from 4.32 to 4.69 t/ha, Dacope (Khulna) from 4.38 to 5.07 t/ha and Amtali (Barguna) from 4.09 to 5.57 t/ha (Table 4). The mean grain yield of rice for the six locations over the treatments were 4.25, 5.68, 5.36, 4.52, 4.67, and 4.64 t/ha, respectively. It reveals that STK demonstrated the highest yield (4.69 t/ha) and FFP exhibited the lowest (4.12 t/ha). Comparing the results for RCM and FRG, similar results were noted for Durgapur, Mymensingh and Thakurgaon locations, but the yield was significantly higher for RCM over FRG at Dacope and Amtali while the reverse was true for Godagari i.e. FRG gave higher yield over RCM. The location average yield was found to be 5.09 t/ha for STK, 4.94 t/ha for RCM, 4.88 t/ha for FRG and 4.51 t/ha for FFP; the grain yields recorded with RCM and FRG were statistically identical.

Table 4. Grain yield (t/ha) of rice in different locations as influenced by different fertilizer doses determined by various methods (Results are the average of 2 years).

Fertilizer rate estimation methods	Durgapur	Godagari	Mymensingh Sadar	Thakurgaon Sadar	Dacope	Amtali	Methods average
FFP	3.96 b	5.23 b	5.07 b	4.32 b	4.38 b	4.09 c	4.51 c
FRG	4.29 ab	5.83 a	5.38 b	4.51 b	4.38 b	4.91 b	4.88 b
RCM	4.19 b	5.49 b	5.46 ab	4.58 ab	4.86 a	5.07 a	4.94 b
STK	4.58 a	6.16 a	5.52 a	4.69 a	5.07 a	4.51 a	5.09 a
F-test	**	**	*	*	**	**	*
Location average	4.25	5.68	5.36	4.52	4.67	4.64	

Note: * Indicate $p < 0.05$. ** indicate $p<0.01$. Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT. FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM = Rice crop manager.

3.3. Economics of Fertilizer Use

Total variable costs include all inputs costs (fertilizers, seedlings, pesticides, irrigation, etc.) and labor costs for operations from land preparation, transplanting etc. to harvest and then processing for marketable produce. Year-wise variable costs are displayed in Table S3 (Supplementary) and the two years' average cost is presented in Table 5 which indicates that the variable costs for STK were US$ 817 followed by 799, 797 and 792 US$ in case of RCM, FRG and FFP, respectively. Fertilizer rates and likely costs varied with the different fertilizer assessment methods. It is noted that generally the fertilizer doses or costs were lower for RCM than STK particularly in saline (Dacope and Amtali) and calcareous soils (Durgapur), but the opposite was the case for the other three locations (Barind, non-calcareous and piedmont soils). However, the costs varied among the methods of fertilizer estimation and obviously between the doses of fertilizer applied for different methods.

Table 5. Total fertilizer costs, gross margin and benefit-cost ratio of crop in different locations as influenced by different fertilizer doses determined by various methods (Results are the average of 2 years).

Location	Total fertilizer costs (US$/ha)				Gross margin (US$/ha)				Benefit-cost ratio			
	FFP	FRG	RCM	STK	FFP	FRG	RCM	STK	FFP	FRG	RCM	STK
Durgapur	93	98	86	102	587	722	672	793	1.63	1.81	1.75	1.86
Godagari	112	103	107	130	734	930	830	1034	1.88	2.13	2.00	2.22
Mymensingh Sadar	52	81	97	77	867	885	841	909	2.07	2.05	1.94	2.05
Thakurgaon Sadar	117	98	65	106	739	805	828	870	2.00	2.16	2.20	2.21
Dacope	77	84	78	98	531	528	678	688	1.70	1.69	1.89	1.87
Amtali	55	79	52	108	363	502	569	397	1.51	1.69	1.78	1.52

Note: FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, RCM = Rice crop manager, STK=Soil testing kit.

Gross return calculated from the price of rice grain and straw against each treatment is presented for year-wise data in Table S4 (Supplementary). Like crop yield, the gross return was relatively lower in saline zones (Dacope and Amtali) that was followed by piedmont plain (Thakurgaon), and gross return for the other three locations (Dur-gapur, Godagari and Mymensingh) was relatively higher. For all locations except Amtali, the STK recorded the highest gross return (US$ 1,598) and FFP had the lowest return (US$ 1,434). The gross return in Durgapur ranged from US$ 1,517 to 1,709, Godagari US$ 1,567-1,879, Mymensingh US$ 1,676-1,772, Dacope US$ 1,290-1,479 and in Amtali the return was US$ 1,078- 1,294 per ha (Table 5).

The year-wise values of gross margin for different fertilizer recommendation tools and locations are shown in Table S5 (Supplementary) and 2-year average results are displayed in Table 5. The gross margin followed the trend: STK > RCM = FRG > FP. For locations, the gross margin followed the order: Godagari > Mymensingh > Thakurgaon > Durgapur > Dacope > Amtali indicating that gross margin in saline regions was relatively lower which can be attributed to lower yield. The gross margin in Durgapur ranged between 587 and 793 US$, Godagari between 734 and 1034 US$, Mymensingh between 841 and 909 US$, Thakurgaon between 739 and 870 US$, Dacope between 531 and 688 US$ and in Amtali it was between 363 and 569 US$ per ha.

4. Discussion

We tested the performance of FRG, RCM, and STK in determining the fertilizer requirements of monsoon rice compared to FFP. Additionally, we assessed the total fertilizer costs, gross margin, and benefit-cost ratio of the crop in different locations for various fertilizer doses determined by each method. Although performance of the STK method was better than FRG, the lack of a profitable business model for operators has prevented its widespread use by farmers. Consequently, we recommend the distribution of pertinent FRG information to farmers through the implementation of FRG Cards. These cards would contain information on fertilizer requirements for each crop, providing a simple and adoptable technology to enhance farmers' decision-making regarding fertilizer usage.

4.1. Effects of Methods of Fertilizer Rate Estimation on Rice Yield

The different rates of application of fertilizers produced differences in rice yield but the STK method consistently had the highest grain yield while the FFP had the lowest. For the other two methods (FRG and RCM), the yield was comparable over the locations. Thus, the grain yield followed the order of STK > RCM = FRG > FFP (Table 4). Overall, the STK yield was 0.5-1.0 t/ha higher than the FFP yield.

The potential yield (same as FRG target yield) of rice varieties used in this study is 5.0 ± 0.5 t/ha. Hence, the STK method enabled rice to reach the potential yield in all locations, the RCM in all places except Durgapur, FRG in all locales except Durgapur and Dacope, and FFP in only two locations, Godagari and Mymensingh.

4.2. Relationship Between Fertilizer Estimation Methods in Terms of Rice Yield

All the methods of fertilizer rate assessment showed significant and positive correlation between each other indicating that yield trend for every method over the locations was similar. It is noted that STK is most correlated with the other methods and FFP is very less correlated (Table 6). The highest correlation occurs between FRG and STK (r=0.813) because both methods are soil analysis based; the STK value is from fresh soil sample analysis while the FRG from an average of historical soil test value of a whole AEZ.

The yield differences among the methods were assessed by 't' statistics. It reveals that the yield increase over FFP for all other methods was statistically significant. Specifically, STK showed significance at the 0.1% level, RCM at the 1% level, and FRG at the 5% level of significance while the increases as a percentage were 12.9%, 9.6% and 8.3% higher over FFP, respectively. The average yield differences of FRG versus RCM, FRG versus STK, and RCM versus STK across the locations were not significant (Table 6).

Table 6. Correlation and 'T' statistics to determine the relationship between fertilizer estimation methods with respect to rice yield (n=72, 6 locations, 2 years).

Fertilizer rate estimation methods	'r' value	't' value+
FFP vs FRG	0.750***	2.64*
FFP vs RCM	0.745***	3.08**
FFP vs STK	0.780***	4.10***
FRG vs RCM	0.756***	0.43
FRG vs STK	0.813***	1.46
RCM vs STK	0.771***	1.05

Note: *, P<0.05; **, P<0.01; ***, p<0.001.
+ Pairwise treatment comparisons by Tukey's HSD method.

4.2. Relationship Between Nutrient Rates Determined by Different Methods and Rice Yield

The rate of different nutrients (N, P, K, S & Zn) for rice production was determined by four methods. Their indi-vidual contribution to rice yield is evaluated by mixed-effects linear regression models and a t-test that uses Sat-terthwaite's method (Table 7). All the nutrients except P had positive contribution to rice yield in the decreasing order of K> Zn> N> S: rates of P had a negative effect on yield. Statistically, the effect of P, K and Zn on rice yield was significant. Noticeably the FFP-P dose was 2-3 times higher than that of other methods' dose in all locations except Mymensingh where RCM-P dose was 2 times higher than FFP-P dose. On the other hand, the STK-K dose was 2-3 times higher than the RCM-K dose in all places except Godagari where it was about 10 kg/ha lower compared to RCM-K. Probably the low estimation of K rates accompanied with inconsistency yield performances across the locations is a weakness of RCM method. Additional research to improve the calibration of the RCM K rates may improve its utility as a recommendation tool. Like RCM, a major weakness of FRG method is the low valuation of K dose. The next revision of the FRG may need to increase the recommendations for K as suggested by Islam, et al. [2] and Islam, et al. [19]. Furthermore, nutrient balance studies show that negative K balance is quite large and that increases in K rate by 25 to 50% can increase crop yield [19, 20]. The FFP method has failed to offer potential yield presumably due to use of very high dose of P, low or no application of Zn and low or high rate of S application (Table 2). Interestingly, all the N doses were similar, with only a 10% variation among the methods.

Table 7. Correlation and 'T' statistics to determine the relationship between nutrient rates with respect to rice yield (n=24, 6 locations, 4 fertilizer methods).

Fertilizer rate	'r' value	't' value (n=24) (Satterthwaite's method)
Yield vs N rate	0.253	1.49
Yield vs P rate	-0.380*	-3.39**
Yield vs K Rate	0.242	2.32*
Yield vs S rate	0.178	0.39
Yield vs Zn rate	0.181	2.14*

Note: *, P<0.05; **, P<0.01.

The initial soil analysis indicated consistently low to very low levels of soil exchangeable K across all study locations [13]. A study estimated the relationship between grain yield and nutrient accumulation in dry matter of irrigated rice, especially focusing on harvest index values ≥0.4. Predicted reciprocal internal efficiencies (RIEs) at 60–70% of yield potential corresponded to specific nutrient accumulations. For irrigated rice with a harvest index ≥0.4, the estimated accumulation per ton of grain yield included 14.6 kg of N, 2.7 kg of P, and 15.9 kg of K [8]. Based on that consideration, we estimate that the uptake by rice grain could range from 66 to 74 kg N /ha, 12-14 kg P /ha and 72-81 kg K/ha. It is important to note that the K uptake for a rice crop may be considerably higher, given that the concentration of K in rice straw is generally more than four times that in the grain [21]. While a portion of the K uptake is anticipated to be supported by the soil (though the exact amount remains unknown due to the absence of a K control), irrigation water, and accretion from rainfall [19] the remaining requirement must be fulfilled through the application of K fertilizer (MoP).

Inadequate application of K also restricts the N uptake which lowers N use efficiency and increases the leaching risk of soluble forms of N. Most of the K in soil is chemically bound in insoluble forms and is slowly available for plant growth. This is especially true in soils that have been depleted due to continuous farming [22]. While a rice crop removes a large amount of K from soil for growth of straw and less through grain, some of the straw K is recycled to soils. Increased crop residue retention as in Conservation Agriculture practice increases the K recycling to soil and decreases the magnitude of negative K balance. Panaullah, et al. [23] reported highly negative K balance for rice-based cropping system in Bangladesh. Recently Hasan, et al. [24] reported an area of 0.287-2.43 Mha (out of 8.87 Mha arable land) have very low to low K status.

4.4. Economic Benefits for Different Methods of Fertilizer Requirement Assessment

The fertilizer cost in STK method was highest in four locations - Durgapur, Godagari, Dacope and Amtali – but not in Mymensingh and Thakurgaon. For the case of FFP, fertilizer cost was the lowest in Durgapur, Mymensingh, Dacope and Barguna. Across all locations, average fertilizer cost follows the order: STK>FRG>FFP>RCM, with an overall variation of 10-20%. So, although the cost variation from different fertilizer management strategies methods was not large, due to more effective balances of nutrients supplied, the impact on rice yield was substantial. Hence, the highest BCR was for STK (1.96) and the lowest for FFP (1.8), while BCR for both RCM and FRG was 1.92 (Table 5). The consistent benefit from the STK method of fertilizer requirement assessment was due to a combination of reasonable fertilizer costs with higher income from output sales. Improved economic performance of any practice is an important factor for farmer adoption [25]. Hence based on profitability, the STK method of fertilizer requirement assessment was expected to be most attractive to farmers but other factors as discussed below mitigated against its acceptance by farmers.

4.5. Adoption of Fertilizer Recommendation Information by Farmers

To gain widespread adoption, a fertilizer recommendation system must effectively tackle the dual challenges of optimizing recommendations for both yield and profit, while also ensuring acceptance among farmers for various crops and cropping patterns. The endorsement of such a system by policies is crucial for its success. In Bangladesh, and in many other nations, the transfer of crop technologies primarily occurs through government-funded agricultural extension agencies. Despite this established pathway, , a substantial percentage (60-85%) of Bangladeshi farmers do not adhere to fertilizer recommendations provided by the Fertilizer Recommendation Guide (FRG) [2]. Consequently, the current extension system appears to be falling short in effectively disseminating fertilizer management technology to farmers. Furthermore, while STK method demonstrated superior performance compared to both FRG and RCM, practical challenges hinder its widespread implementation. Operating the soil test involves continual procurement of chemicals and demands skilled personnel for handling. Unfortunately, establishing a profitable business model for making the STK widely accessible to smallholder farmers remains elusive. Inconsistent results of the current RCM method discourage its promotion to farmers. As discussed above, further research to improve its calibration for N, P, K, S and Zn fertilizer recommendations may improve its utility and adoptability.

Hence, we explored the FRG as an alternative, effective and adoptable method of disseminating information. To address the issue, we developed FRG Cards taking information from the latest Fertilizer Recommendation Guide [13] and tested them with farmers. Across the ten project hubs, 33,237 (including 1,336 women farmers) farmers received FRG Cards followed by a short training session (about 20 mins each) for use in cropping on 21,160 ha of arable land. An evaluation was done to assess the effectiveness of the FRG card in disseminating FRG information to the farmers [26]. The key findings were as follows: (i) 100% of respondents were familiar with FRG Card, but less than 50% with STK and RCM, (ii) about 95% of the FRG Card holders followed the recommendation of Bangladesh Agricultural Research Council (BARC) [13] in T. Aman rice due to user-friendliness, and (iii) a small percentage of farmers used Soil Testing Kit (STK).

Hence, FRG Card when provided with training to the farmers was accessible, while applying the FRG information in their crops increased aman rice grain yield by 84% and net profit increased by 143% over FFP. The next step is to scale-out the use of the FRG Card by larger numbers of farmers. This will require lower cost methods of distributing the FRG Card and training farmers in its use including mass media and social media.

5. Conclusion

The study indicates that the STK (Soil Testing Kit developed by Bangladesh Agricultural University, Mymensingh) had the best performance with regard to rice yield and gross margin. Next to it was the Fertilizer Recommendation Guide (FRG) based on agroecological zone-specific recommendation. In contrast, the Rice Crop Manager (RCM) did not consistently yield reliable results. A notable weakness observed across all three methods was the consistent underestimation of potassium (K) requirements, except for the STK method, which directly assessed the current soil K availability. This underestimation of K needs is a common issue in subtropical Asia, where rice cropping systems deplete substantial amounts of K annually, leading to an increasing demand for K fertilizer over time. Although performance of the STK method was better than FRG, the lack of a profitable business model for operators has prevented its widespread use by farmers. Previous barriers to supplying relevant FRG information to farmers can be overcome by providing necessary packaged information on fertilizer requirements for each crop to farmers in the form of a FRG Card. The FRG Card is a simple and adoptable technology for improved fertilizer decision-making by the farmers.

Abbreviations

The following abbreviations are used in this manuscript:

%	Percentage
AEZ	Agro-ecological zones
BAU	Bangladesh agricultural university
cmol	Centimole
DMRT	Duncan's multiple range test
FAO	Food and Agriculture Organization of United Nations
FFP	Farmer fertilizer practice
FRG	Fertilizer recommendation guide
GPS	Geo-graphical Positioning System
ha	Hectarage
K	Potassium
kg	Kilogram
mg	Milligram
Mha	Million hectarage
MoP	Muriate of Potash
N	Urea
NUMAN	Nutrient Management for Diversified Cropping in Bangladesh
P	Phosphorus
RCBD	Randomized complete block design
RCM	Rice crop manager
S	Sulphur (gypsum)
SSNM	Site-specific nutrient management
STK	Soil testing kit
t	Tonne
t/ha	Ton per hectarage
Tk.	Taka
TSP	Triple superphosphate
UNDP	United nations development program
US$	US dollar
Zn	Zinc sulphate fertilizer

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Table S1. Estimation of rates of urea, TSP, MoP, gypsum and zinc sulphate fertilizers based on four different methods and locations for use in T. Aman rice cultivation in 2018 and 2019.

Location	Treatment	Fertilizer dose (kg/ha)									
		Urea		TSP		MoP		Gypsum		Zinc sulphate	
		2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Durgapur, Rajshahi	FFR	76	341	151	110	76	82	0	58	3.3	7.5
	FRG	197	158	50	35	71	81	76	34	2.7	6.5
	STK	197	197	40	40	151	151	62	62	0.0	12.2
	RCM	180	244	44	59	39	57	19	38	1.4	7.5
Godagari, Rajshahi	FFR	221	250	72	81	72	75	83	50	4.0	1.2
	FRG	199	196	57	50	100	150	50	44	2.8	0.0
	STK	199	195	15	15	138	74	75	74	12.2	12.1
	RCM	257	263	56	66	60	59	42	41	8.4	5.6
Sadar, Mymensingh	FFR	97	125	57	69	38	80	0	6	0.0	0.0
	FRG	198	198	51	40	71	101	64	22	2.8	4.5
	STK	197	197	40	52	151	126	0	62	0.0	12.2
	RCM	354	265	178	68	70	65	0	38	0.0	7.5
Sadar, Thakurgaon	FFR	214	227	71	118	71	122	0	157	7.1	10.9
	FRG	186	198	48	36	57	101	60	34	2.6	6.5
	STK	186	197	37	64	104	155	47	50	11.6	6.5
	RCM	157	155	63	34	98	45	36	34	7.1	6.5
Dacope, Khulna	FFR	132	175	89	84	85	84	47	0	0.0	0.0
	FRG	165	198	51	76	36	101	25	23	2.8	4.5
	STK	198	197	40	70	78	100	25	50	2.8	12.3
	RCM	163	163	43	54	43	54	43	54	0.0	4.5
Amtali, Barguna	FFR	250	125	125	76	0	0	0	0	0.0	0.0
	FRG	165	158	51	35	37	80	25	13	2.8	5.0
	STK	198	198	70	60	151	111	0	50	0.0	12.3
	RCM	250	125	62	28	36	30	0	13	0.0	5.0

Note: FFR=Farmer's fertilizer rate, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM=Rice crop manager
MoP=Muriate of potash, TSP = Triple superphosphate.

Table S2. Grain yield (t/ha) of T. Aman rice in different locations and years as influenced by different fertilizer doses determined by various methods in 2018 and 2019.

Fertilizer tools	Durgapur, Rajshahi	Godagari, Rajshahi	Mymensingh, Sadar	Thakurgaon Sadar	Dacope, Khulna	Amtali, Barguna
			2018			
FFP	3.76b	4.95b	4.56	3.55	3.48b	3.47b
FRG	3.98ab	5.51a	4.68	3.6	3.57b	3.79ab
STK	4.14a	5.75a	4.59	3.66	3.99a	3.67b
RCM	3.95ab	5.29ab	4.38	3.81	4.19a	4.23a
F-test	**	**	NS	NS	**	**
			2019			
FFP	3.50b	4.55b	4.86b	4.3	4.48b	3.99c
FRG	3.81ab	5.09ab	5.1b	4.61	4.39b	5.14a
STK	4.19a	5.46a	5.45a	4.87	5.24a	4.52b
RCM	3.68b	4.69b	5.56a	4.52	4.65b	5.00a
F-test	**	**	**	NS	**	**

Note: ** indicate p<0.01; NS = Not significant.
Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of prob ability by DMRT.
FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM = Rice crop manager.

Table S3. Variable costs (USD/ha) of T. Aman rice in different locations and years as influenced by different fertilizer doses determined by various methods in 2018 and 2019

Fertilizer tools	Durgapur, Rajshahi	Godagari, Rajshahi	Mymensingh, Sadar	Thakurgaon Sadar	Dacope, Khulna	Amtali, Barguna
2018						
FFP	785	833	778	710	762	786
FRG	791	815	815	709	749	763
STK	795	840	810	731	761	789
RCM	767	829	891	717	748	773
2019						
FFP	1074	833	840	767	756	643
FRG	1001	830	869	681	780	697
STK	1,38	851	917	704	821	743
RCM	1025	835	897	661	774	676

Note: NS = Not significant.
Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT.
FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM = Rice crop manager.

Table S4. Gross return (USD/ha) of T. Aman rice in different locations and years as influenced by different fertilizer doses determined by various methods in 2018 and 2019

Fertilizer tools	Durgapur, Rajshahi	Godagari, Rajshahi	Mymensingh, Sadar	Thakurgaon, Sadar	Dacope, Khulna	Amtali, Barguna
2018						
FFP	1.748	2.120	1.989	1.822	1.409	1.317
FRG	1.841	2.374	2.015	1.807	1.437	1.410
STK	1.897	2.545	2.001	1.902	1.601	1.384
.	1,799	2.269	1.933	1.865	1.668	1.559
2019						
FFP	1.285	1.014	1.363	1.133	1.171	838
FRG	1.395	1.131	1.439	1.193	1.148	1.054
STK	1.521	1.213	1.543	1.273	1.356	942
RCM	1.337	1.054	1.537	1.169	1.209	1.028

Note: NS = Not significant.
Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT.
FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM = Rice crop manager.

Table S5. Gross margin (USD/ha) of T. Aman rice in different locations and years as influenced by different fertilizer doses determined by various methods in 2018 and 2019

Fertilizer tools	Durgapur, Rajshahi	Godagari, Rajshahi	Mymensingh Sadar	Thakurgaon Sadar	Dacope, Khulna	Amtali, Barguna
2018						
FFP	963	1287	1211	1112	647	531
FRG	1050	1559	1200	1098	688	647
STK	1102	1705	1191	1171	840	595
RCM	1032	1440	1042	1148	920	786
2019						
FFP	211	181	523	366	415	195
FRG	394	301	570	512	368	357
STK	483	362	626	569	535	199
RCM	312	219	640	508	435	352

Note: NS = Not significant.
Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT.
FFP = Farmer fertilizer practice, FRG=Fertilizer recommendation guide, STK=Soil testing kit, RCM = Rice crop manager.