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Potassium Supplying Capacity of Diverse Soils and K-Use Efficiency of Maize in South Asia

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Abstract: Increased nutrient withdrawal by rapidly expanding intensive cropping systems, in combination with imbalanced fertilization, is leading to potassium (K) depletion from agricultural soils in Asia. There is an urgent need to better understand the soil K-supplying capacity and K-use efficiency of crops to address this issue. Maize is increasingly being grown in rice-based systems in South Asia, particularly in Bangladesh and North East India. The high nutrient extraction, especially K, however, causes concerns for the sustainability of maize production systems in the region. The present study was designed to estimate, through a plant-based method, the magnitude, and variation in K-supplying capacity of a range of soils from the maize-growing areas and the K-use efficiency of maize in Bangladesh. Eighteen diverse soils were collected from several *upazillas* (or sub-districts) under 11 agro-ecological zones to examine their K-supplying capacity from the soil reserves and from K fertilization (@ 100 mg K kg⁻¹ soil) for successive seven maize crops grown up to V10-V12 in pots inside a net house. A validation field experiment was conducted with five levels of K (0, 40, 80, 120 and 160 kg ha⁻¹) and two fertilizer recommendations based on “Nutrient Expert for Maize-NEM” and “Maize Crop Manager-MCM” decision support tools (DSSs) in 12 farmers’ fields in Rangpur, Rajshahi and Comilla districts in Bangladesh. Grain yield and yield attributes of maize responded significantly ($P < 0.001$) to K fertilizer, with grain yield increase from 18 to 79% over control in all locations. Total K uptake by plants not receiving K fertilizer, considered as potential K-supplying capacity of the soil in the pot experiment, followed the order: Modhukhali > Mithapukur > Rangpur Sadar > Dinajpur Sadar > Jhinaidah Sadar > Gangachara > Binerpota > Tarash > Gopalpur > Daudkandi > Paba > Modhupur > Nawabganj Sadar > Shibganj > Birganj > Godagari > Barura > Durgapur. Likewise in the validation field experiment, the K-supplying capacity of soils was 83.5, 60.5 and 57.2 kg ha⁻¹ in Rangpur, Rajshahi, and Comilla, respectively. Further, the order of K-supplying capacity for three sites was similar to the results from pot study confirming the applicability of results to other soils and maize-growing areas in Bangladesh and similar soils and areas across South Asia. Based on the results from pot and field experiments, we conclude that the site-specific K management using the fertilizer DSSs can be the better and more efficient K management strategy for maize.

Keywords: Site-specific K management, Soil K supply, Maize yield response to K, Maize Crop Manager, Nutrient Expert for Maize.

1. Introduction

Maize is the second most important cereal crop after rice in Asia and provides approximately 30% of the food calories to more than 4.5 billion people in 94 developing countries [1]. The world population is increasing and will continue to increase from 7.2 to 8.1 billion by 2025, reaching 9.6 billion by 2050 and 10.9 billion by 2100, with most growth occurring in the developing countries [2,3]. Maize was grown in 0.36 million hectares during 2014-15 in Bangladesh [4].

Available soil K is deficient in many soils of Bangladesh, and crops are showing K deficiency symptoms. It is well known that the availability of K to plants does not only depend on the size of the available pool in the soil but also on the transport of K from soil solution to the root zone and from the root zone into plant roots [5]. Many plant factors (variety, root system, and antagonistic and synergistic mechanisms in ion uptake), soil factors (pH, organic matter content, texture, complementary cations, etc.) and environmental factors (rainfall, temperature, etc.) may affect these processes. However, when plant available soil K is sufficient, these factors tend to become less important. Therefore, soil K-supplying capacity is a key factor to sustain and increase crop yields.

Recent soil-test results have shown that many soils of the Indo-Gangetic Plains (IGP) of South Asia, with available K concentration of less than 0.1 cmol kg⁻¹, are becoming deficient in K despite their original high K contents [6–10]. The introduction and prevalence of high yielding varieties of rice, hybrid maize and wheat since the green revolution accelerated the removal of K from the soil than the traditional varieties did. At the same time, the application of K fertilizers, on the other hand, was limited, leading to negative input-output balance of K that depleted soil K status in most of the Asian countries [10,11]. Scientists reported 31% decline in soil K status in Bangladesh over the past 30 years, which is an alarming figure [12]. Despite this, studies in soil K received less attention than other major nutrients, because the application of K fertilizer doesn't frequently bring about a dramatic improvement in the vegetative growth of crop as is observed with N fertilizer, or does not have the environmental concerns associated with its use as in N. Besides, the general perception that the South Asian soils are rich in K-bearing minerals also led to the complacency that crops may not require external K application to perform adequately. Therefore, most of the farmers, who can afford to apply fertilizers to their crops, apply only urea and phosphatic fertilizers, while K application is often neglected. As a result, soils which were not deficient in K in the past have either become deficient or are likely to become deficient in the near future [13].

Of the three main macronutrients (N, P, and K), much work has been done in the past about N management in cropping systems [14,15]. The focus now, however in the context of maize production has been shifted to K nutrition, as the K dynamics of maize-growing soils dictate how well the K demand for high-yielding maize crops can be met. It is hypothesized that soils of maize-growing areas in Bangladesh differ in terms of mineralogy, soil K reserves, allowable drawdown, and K-supplying capacity. Thus, some soils would require more while others would require less K to grow profitable maize crops. Carefully-conducted pot and field experiments using a plant-based assay are expected to help estimate the magnitude and variation in K-supplying capacity of soils. The information generated from such experiments would help develop soil-based coefficients on allowable draw down of soil K reserves, which can be used for the determination of fertilizer K requirements of maize for Bangladesh, as well as for other maize-growing areas in South Asia.

Soil indigenous K supply, K-use efficiency, and crop yield vary spatially and temporally in the diverse irrigated maize fields in Bangladesh and South Asia. At present, however, blanket fertilizer recommendations are often applied over large areas without taking into account the wide variability in site- and season-specific crop nutrient requirements, which explains the reasons for low K-use efficiency. Further, the use of K fertilizers is often not based on crop requirements, and are not balanced with other nutrients. As a result, the profitability is not optimized [6,16]. A rational and profitable K fertilizer management strategy needs to be based on better understanding of the soil K-supplying capacity. The efficiency of applied K fertilizer, in terms of agronomic efficiency of K (AE_K, kg yield increase per kg nutrient applied) and apparent K recovery efficiency (RE_K, kg K uptake per

kg K applied) are commonly used as performance indicators for K management strategies [17–19]. The K-use efficiency is generally affected by yield levels, soil indigenous K-supplying capacity, amount of K fertilizer applied, and the quality of crop management operations [18]. Keeping the above points in view, the present study was undertaken to i) determine the indigenous K-supplying capacity of major maize-growing soils in Bangladesh, and ii) evaluate the grain yield and the K-use efficiency for maize under different K fertilizer recommendation strategies in the diverse soils of Bangladesh.

2. Materials and Methods

2.1 Pot Experiment

2.1.1 Experimental soils

Soil samples (0 to 20-cm) were collected from farmers' fields of 18 *upazillas* or sub-districts (representing 18 diverse soils) located in the North, North-west, East, and South parts of Bangladesh. The 18 *upazillas* were: Birganj, Dinajpur Sadar, Gangachara, Rangpur Sadar, Mithapukur, Shibganj, Godagari, Paba, Durgapur, Tarash, Gopalpur, Modhupur, Daudkandi, and Barura (Figure 1). The soil samples were air-dried, ground and sieved through 2 mm sieve, and subject to test for their properties. Soil pH was determined in 1:1 soil/water paste by a pH meter. Exchangeable K was extracted by 1 mol L⁻¹ NH₄OAc, non-exchangeable K by boiling HNO₃ method, and total K by HF digestion [20]. Particle size analysis was done by Hydrometer method [21] and the textural class was determined from Marshall's triangular co-ordinate following USDA system. The physical and chemical properties of the tested soils from the various *upazillas* used for pot study are presented in Table 1, while that for field experiment are presented in Table 2.



Figure 1. Dots showing the locations of soil samples collected for pot experiment and stars showing the field experimental sites in Bangladesh

Table 1. Basic chemical and physical properties of soil for the three field experimental sites before sowing of rabi (winter) maize, 2012-13.

Location	AEZ	Previous crop	pH	OC (%)	Total N (%)	P	K _{sl}	K _{ex}	K _{nex}	S	Soil particles (%)			Texture
											mg kg ⁻¹ soil			
											Sand	Silt	Clay	
Birganj	1	Potato	5.85	1.29	0.088	84.46	25	57	1475	6.28	70	18	12	Sandy loam
Dinajpur Sadar	3	Rabi maize	5.89	0.98	0.064	12.27	40	83	1608	6.15	62	21	17	Sandy clay loam
Gangachara	2	Rabi maize	5.83	1.29	0.091	51.47	38	76	1544	5.91	33	50	17	Loam
Rangpur Sadar	3	Potato	6.64	0.27	0.03	19.44	45	99	2220	6.4	51	27	22	Sandy clay loam
Mithapukur	3	Rabi maize	5.9	1.48	0.107	77.29	60	113	3098	5.17	37	31	32	Loam
Shibganj	4	Boro rice	6.18	0.86	0.054	21.2	26	63	1876	6.77	41	24	35	Clay loam
Godagari	11	Boro rice	6.68	1.13	0.077	7.97	28	76	996	7.51	43	23	34	Clay loam
Nawabganj	11	Boro rice	7.15	1.4	0.1	3.82	58	83	970	6.52	47	28	25	Sandy clay loam
Paba	11	Rabi maize	7.25	1.76	0.131	6.06	60	85	1080	8.37	41	28	31	Clay loam
Durgapur	11	Boro rice	7.16	1.17	0.081	14.34	20	62	845	8.37	31	54	15	Silt Loam
Tarash	7	Boro rice	6.06	1.09	0.074	5.74	46	99	1345	7.75	25	36	39	Silty clay
Gopalpur	8	Boro rice	5.84	1.83	0.137	5.42	30	90	871	6.28	44	24	32	Clay loam
Modhupur	28	Boro rice	5.83	1.25	0.088	3.67	35	89	761	5.66	26	44	30	Clay loam
Modhukhali	12	Boro rice	7.51	1.76	0.13	1.91	105	124	2357	13.05	23	15	62	Clay
Binerpota	13	Boro rice	7.24	1.85	0.139	3.19	80	101	2145	13.05	24	12	64	Clay
Jhinaidah Sadar	11	Boro rice	6.97	1.91	0.144	3.98	75	100	2065	13.41	37	31	32	Clay loam
Daudkandi	16	Rabi maize	6.78	0.82	0.051	47.65	35	60	1123	12.06	43	15	42	Loam
Barura	19	Rabi maize	7.06	1.33	0.094	20.4	22	58	1060	7.38	47	17	36	Loam
Range			5.8-	0.27-	0.03-	1.91-	20-	57-	761-	5.17-	-	-	-	-
					7.5	1.91	0.14	84.46	105	124	3098	13.41		

Table 1. Chemical and physical properties of soil in field experimental sites before sowing of rabi (winter) maize, 2012-13.

Soil properties	Methods of determination	Rangpur (n=4)			Rajshahi (n=4)			Comilla (n=4)		
		Mean	Range	SD	Mean	Range	SD	Mean	Range	SD
pH	By pH meter	5.78	5.46-5.96	0.22	5.94	5.18-6.66	0.80	5.23	5.10-5.38	0.15
SOC (%)	Wet digestion method	2.00	1.27-3.22	2.00	1.29	1.14-1.34	0.10	1.90	1.21-2.82	0.70
Total N (%)	Micro-Kjeldahl distillation	0.09	0.06-0.14	0.03	0.06	0.06-0.07	0.01	0.09	0.06-0.13	0.03
Available P (mg kg ⁻¹)	Modified Olsen's method	12.53	10.24-14.02	1.63	13.44	12.0-15.9	1.77	11.88	8.54-15.08	3.41
K _{ex} (mg kg ⁻¹)	1 M NH ₄ OAc method	41.34	37.44-43.29	2.68	44.85	43.29-47.19	1.77	38.22	28.47-54.21	11.33
K _{nx} (mg kg ⁻¹)	1 M HNO ₃ method	1269	1061-1439	197	858	827-870	21	987	857-1057	89
Available S (mg kg ⁻¹)	By 0.15 % CaCl ₂ extraction	14.94	12.9-17.08	2.02	15.57	13.69-18.12	2.03	13.29	11.96-15.24	1.47
Soil textural class	Hydrometer methods	Silt loam			Silt loam			Silt loam		
Sand (%)		43.00	36-60	11.49	39.25	26-68	19.38	39.00	34-63	15.37
Silt (%)		54.75	39-63	10.72	54.00	29-67	17.17	54.00	32-62	14.08
Clay (%)		2.75	2-5	1.50	7.00	4-10	2.45	6.00	3-9	2.83

2.1.2 Description of pot experiment

A repeated pot experiment was conducted with the eighteen soils using a randomized complete block experimental design that consisted of a no-K fertilizer (K0) and a 100 mg K kg⁻¹ soil (K100) treatments in four replications in a net house of Bangladesh Rice Research Institute (BRRI), Gazipur. Soils were air dried and ground to pass a 2-mm sieve, and 7 kg of each soil was weighed into each pot. Other fertilizers such as urea, TSP, gypsum, and zinc sulfate were used in every pot to supply N, P, S and Zn @ 200, 50, 10, and 5 mg pot⁻¹, respectively. All nutrients except N were applied before sowing of maize while N was applied in two splits. After application of fertilizers, the soil was gently irrigated allowing smooth mixing of fertilizer materials with soils. After basal fertilizer application, five healthy seeds of hybrid maize (cv. BARI Hybrid Maize-8) were sown two cm below soil surface in each pot. Seeds were germinated after 6-11 days of sowing. Emergence was delayed in winter due to low temperature. Thinning was done 5-7 days after emergence, keeping 4 healthy plants per pot. After thinning, half N was top dressed, while the remaining 1/2 was applied at V6 stage (when 6 leaves appeared). The crop was irrigated with tap water as and when required. The aboveground part of the maize plant was cut at the soil surface at V10-V12 stage (55-65 d after emergence) because >90% of the total K uptake is usually accumulated by that stage [22]. The maize tissue was dried at 70°C for 48 h, crushed, and ground to pass a 0.5-mm sieve. A 0.5-g sub-sample was digested by an HNO₃-HClO₄ mixture at 180 to 200°C [23] and K concentration was determined. Soil samples were collected before and after cropping for NHOAc-extractable K determination [20]. Seven maize crops were grown successively in each pot. Climate during the seven maize-growing periods together with crop duration for each period are presented in Figure 2.

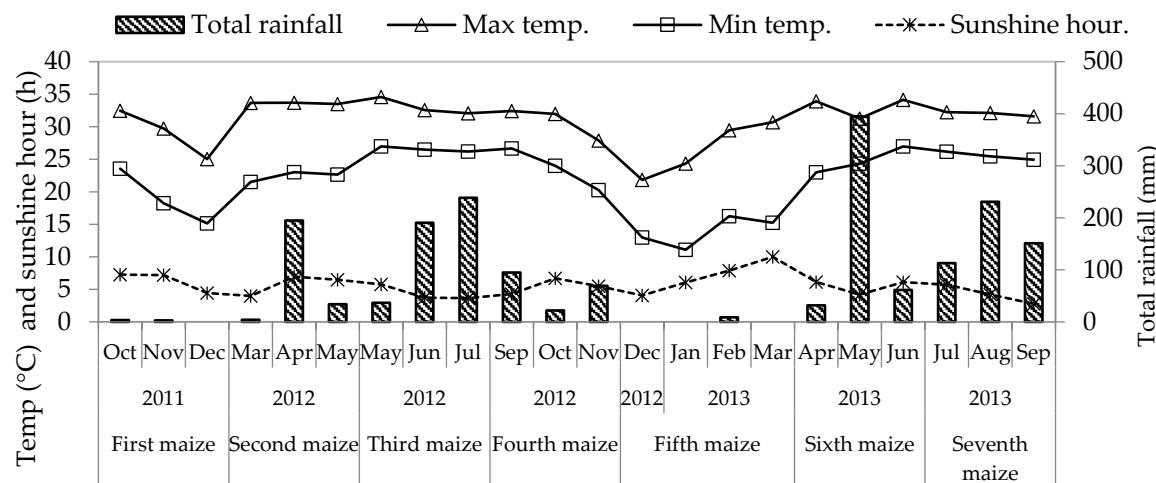


Figure 2. Mean monthly sunshine hour (h), minimum, maximum temperatures (°C), and total rainfall (mm) during successive cropping of *rabi* maize in pot from 2011 to 2013 in Gazipur, Bangladesh.

2.2 Field Experiment

2.2.1 Experimental sites

A field experiment was conducted in 12 farmers' fields in three districts in Bangladesh, with 4 fields each in Rangpur (25.74° N, 89.28° E), Rajshahi (24.36° N, 88.62° E) and Comilla (23.46° N, 91.19° E) (Figure 1). Rajshahi is situated in the Active Ganges Floodplain (agro-ecological zone-AEZ, AEZ 11); Comilla is in the Old Meghna Estuarine Floodplain (AEZ 19); while Rangpur is spread over both the Active Tista Floodplain (AEZ 2) and Tista Meander Floodplain (AEZ 3) [24]. Experimental fields in Rangpur were located in AEZ 3 only.

The four farmers' fields in each district (two *upazillas* per district) were selected based on soil K (ranging from very low to high) across Bangladesh and from the literature review of K status in

Bangladesh soils. The selected farmers' fields represented the diverse agro-ecosystems with variations in the cropping system, soil, and climate within each district.

2.2.2 Climatic condition during the experimental period

The experimental fields were located in sub-tropical to the tropical climate, and the weather data for the three districts during the experimental period are shown in Figure 3. Most of the rainfall at all the sites occurred during the monsoon season (June to October). There was no rain from November 2012 to January 2013 in Rangpur, but Rajshahi and Comilla received ~100 mm rain in November. The total rainfall during the maize season was 532, 373, and 611 mm in Rangpur, Rajshahi, and Comilla, respectively. The mean minimum and maximum temperatures during the maize season were 9 °C and 32 °C, 9 °C and 36 °C, 11 °C and 33 °C in Rangpur, Comilla, and Rajshahi, respectively. The mean minimum and maximum temperatures were 9 °C and 25 °C respectively at the beginning of the experiment in January, with lower temperatures in Rangpur than the other two districts. The temperatures increased steadily to mean a minimum of 22 °C and mean maximum of 36 °C in April and May 2013. Mean sunshine hours across districts ranged from 5.8 to 6.8 hr day⁻¹, with lowest sunshine hours recorded in Rangpur and highest in Comilla. At the beginning of the experiment, the sunshine hour was much lower in Rangpur (2.8 hr day⁻¹) than the other two districts, and as the season progressed, the sunshine hour in all districts increased steadily to maximum of 10.9, 10.6, and 10.3 hr day⁻¹ in Rangpur, Rajshahi and Comilla, respectively (Figure 3).

2.2.3. Fertilizer decision support tools

Based on the principles of site-specific nutrient management (SSNM) and experiences drawn from several years of on-farm research on maize in several Asian countries [25–30], the International Rice Research Institute (IRRI) and International Plant Nutrition Institute (IPNI) developed the fertilizer decision support system (DSS) tools, Maize Crop Manager (MCM) and Nutrient Expert for Maize (NEM), respectively, in collaboration with the International Maize and Wheat Improvement Centre (CIMMYT) and National Agricultural Research and Extension Systems (NARES) partners in South and Southeast Asia. The K fertilizer recommendation rates based on these two fertilizer DSS tools were compared against five levels of K (Table 3).

Table 3. Fertilizer recommendations for three field experimental sites in Bangladesh based on Maize Crop Manager and Nutrient Expert for Maize.

Nutrient	Rangpur (kg ha ⁻¹)		Rajshahi (Kg ha ⁻¹)		Comilla (kg ha ⁻¹)	
	MCM	NEM	MCM	NEM	MCM	NEM
N	184	164-173	184-190	162-173	115-150	141-152
P	20	22-23	15-20	19-25	15-20	19-20
K	88	109-125	75-100	93-105	75-100	93-103
S	7	7	7	7	7	7
Zn	3	3	3	3	3	3
B	1	1	1	1	1	1

2.2.4. Experimental design and treatments

The experiment was laid out in a Randomized Complete Block Design in 12 farmers' fields (serving as replicates) with five K levels ($K_1 = 0$, $K_2 = 40$, $K_3 = 80$, $K_4 = 120$, $K_5 = 160$), and two K fertilizer recommendations based on SSNM (DSS) tools (K_6 = Nutrient Expert based recommendation for maize (NEM); K_7 = Maize Crop Manager based recommendation (MCM)) in three districts. To determine the SSNM-based recommendations using the DSS tools (MCM, <http://webapps.irri.org/bd/mcm/>, and NEM, an offline computer-based software), the participant farmers were asked 20 questions based on their agronomic and nutrient management practices of last (previous) year along with their field

or soil characteristics. The answers to these questions were used as inputs to the MCM and NEM for generating fertilizer recommendations for each farmer (Table 3). Each treatment plot was 50 m² in area. Bunds of 0.5 m width were prepared between plots, and a border of 1 m width was kept around the experimental area. A medium-statured hybrid maize NK40, popularly grown in *Rabi* (winter) season was used. NK40 is tolerant of lodging and has a high yield potential of up to 20 t ha⁻¹.

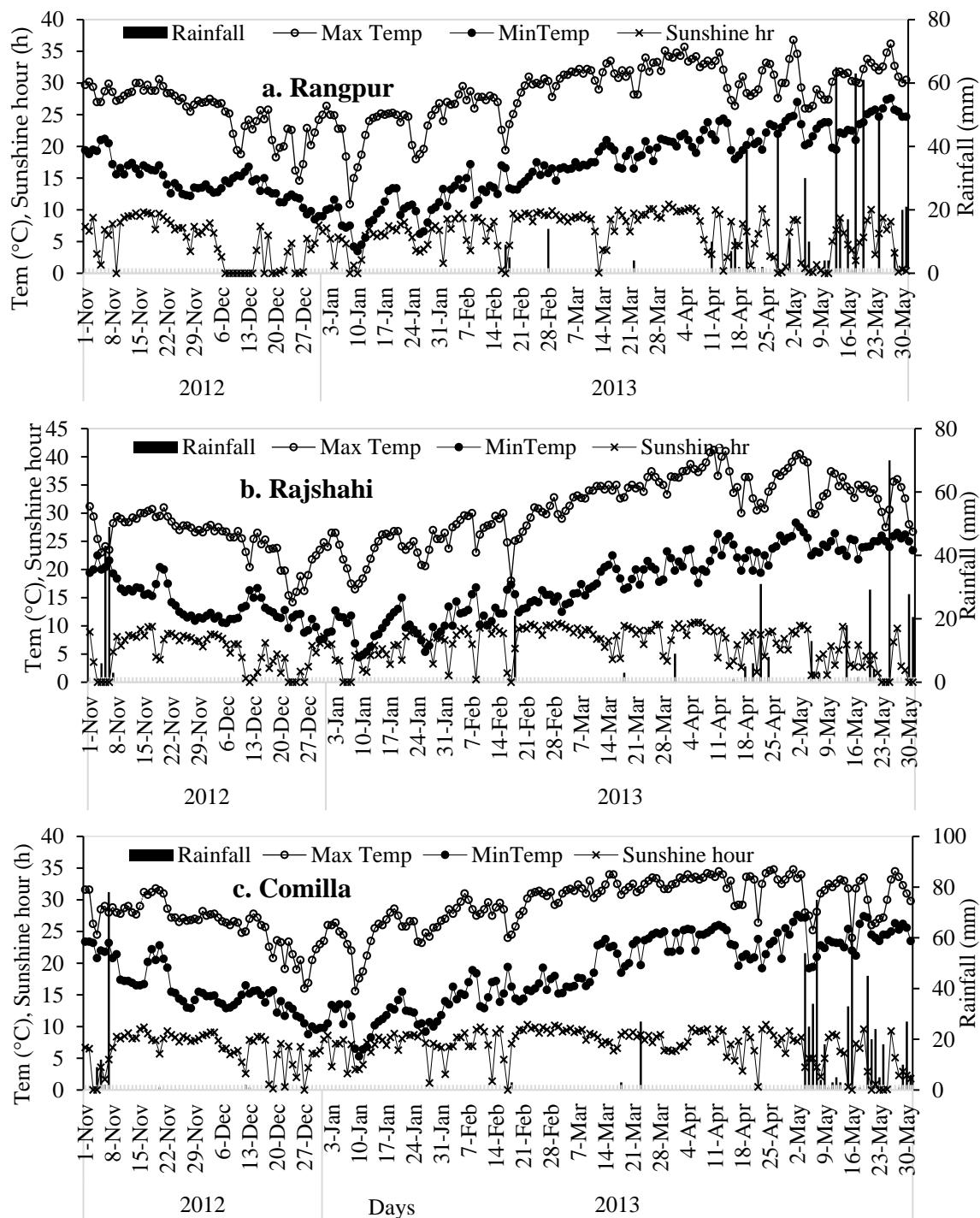


Figure 3: Daily maximum and minimum temperatures (°C), sunshine hour (h) and total rainfall (mm) during the rabi maize season from November 2012 to May 2013 in experimental sites (a. Rangpur, b. Rajshahi, c. Comilla) in Bangladesh.

2.2.5. Crop management practices

The experimental fields in all districts were irrigated with about 10 cm of water and allowed to reach proper moisture condition conducive for tillage. The fields were then prepared by 3-4 tillage with a 2-wheel operated power tiller to a depth of 8-10 cm followed by planking. Seeds in all districts were sown manually (with sowing dates ranging from 26 November 2012 to 6 January 2013) on shallow holes by dibbling and maintaining row to row and seed to seed distances of 60 and 20 cm respectively. Gap filling was done after emergence to maintain the 85,000 plant population ha^{-1} . N, P, K, S, and Zn were applied through urea, TSP, MOP, gypsum and zinc sulfate, respectively. Rates for different nutrients, including K, applied through the recommendations of MCM and NEM are presented in Table 3. N fertilizer was applied as three splits: as basal and top-dressed twice at V6 and V10; while K was applied as two splits: as basal and at V6. All other fertilizers were applied as basal.

The crops were manually weeded twice: the first weeding was done just before the first top dressing while the second was before the second top dressing, thus allowing the weeds to be removed from the fields before each top-dressing. As rainfall was not enough, four irrigations were applied in each site to avoid drought stress to the crops. First irrigation was applied at V2-V4 (2-3 leaves stage) while the second irrigation was applied after first weeding and before first top dressing at V6-V8 (6-8 leaves stage). Likewise, third irrigation was applied after second weeding and before second top-dressing at V10-V12 (10-12 leaf stage) and fourth irrigation during grain formation stage. The amount of water for each irrigation at each site was about 7.5 cm. Carbofuran 10G @ 100g per 100-meter rows was applied at planting for controlling cutworms and nematode infestation.

2.3 Data Analysis and Measurements

The crops were harvested at maturity from a 10.08 m^2 (4.2 m row length by 4 rows) area in the center of each treatment plot, excluding the two outer border rows. After harvesting, the crops were threshed with a hand thresher. The grain and stover yields and the growth and yield attributing characters (plant height, cobs plant^{-1} , cob length and girth, grains cob^{-1} , 1000-grain weight) were measured. The grain and stover samples from each plot were analyzed for total K content. For the post-harvest soil analysis for K_{ex} and K_{nex} , composite soil samples were taken from each treatment of each farmer immediately after crop harvest by using the methods as described in Table 2 [23].

Indigenous K supply (IKS) is defined as the amount of soil K that is available to maize from the soil during its growing period when other nutrients are non-limiting [30], and the IKS can be measured as the K accumulation in the above ground dry matter at harvest in the K omission plots [31]. Yield response (YR) is an effective index of soil fertility, and YR to K is defined as the yield difference between the attainable yield (measured as 85-90% of yield potential) and yield from the K omission plots [25, 26]. YR to K can also be used to evaluate the soil K-supplying capacity [32]. The K concentration (%) of plant samples (stover and grain) was determined by a flame photometer [33].

The data from the K exhaustion study from the pot experiment as well as the field experiments were used to quantify the K-supplying capacity of the 18 soils to maize crops, and was calculated as follows-

$$\text{Total plant K uptake} = \text{above ground biomass} \times \text{K concentration in plant tissue} \quad (2)$$

$$\text{Agronomic efficiency (AE}_K\text{; kg grain yield increase kg}^{-1} \text{ applied K}) \text{ was calculated using the equation: } \text{AE}_K = (G_{Y_K} - G_{Y_{0K}}) / F_K \quad (3)$$

Where GY_{+K} is the grain yield in the treatment with K application (kg ha^{-1}), GY_{0K} is the grain yield in the treatment without K application (kg ha^{-1}), and F_K is the quantity of K applied (kg ha^{-1}).

Recovery efficiency (RE_K ; $\text{kg K taken up kg}^{-1} \text{ K applied}$) was calculated using the equation: $RE_K = (UK_{+K} - UK_{0K}) \div F_K$(4)

Where UK_{+K} is the total plant K uptake (kg ha^{-1}) of the above-ground biomass (stover + grain) in plots that received K, UK_{0K} is total K uptake without the addition of K, and F_K is the quantity of K applied (kg ha^{-1}).

The R software [34,35] was used to analyze the means of grain and stover yields, growth and yield components, total K uptake, agronomic efficiency and recovery efficiency of K between different soils and treatments by using the least significant difference at 0.05 probability level. The Duncan's New Multiple Range Test, a mean separation technique, was applied to detect significant differences between treatment [36].

3. Results

3.1 Pot Experiment

3.1.1 Mean shoot dry matter yield and yield response to K fertilizer

The mean shoot dry matter yield of maize over seven successive cropping across 18 soils varied widely from 14.52 to 39.37 g pot^{-1} in K control pots while it was from 38.83 to 47.81 g pot^{-1} in K applied pots. The lowest and highest dry matter yield with no added K soils were found in Durgapur and Mithapukur soils, respectively. While the lowest and highest dry matter yield with K fertilizer added soils were found in Modhupur and Gopalpur soils, respectively (Figure 4). The contribution of K fertilizer to the increment of maize shoot dry matter over K control was considered as the shoot dry matter response to K. The mean response of shoot dry matter over seven successive cropping ranged from 4 to 16 g pot^{-1} , with the highest response ($P \leq 0.001$) in Durgapur soil and the lowest in Modhukhali. The mean response followed the order of: Durgapur > Shibganj > Barura > Godagari > Tarash > Paba > Binerpota > Jhinaidah Sadar > Modhupur > Birganj > Nawbagnj Sadar > Gopalpur > Daudkandi > Gangachara > Rangpur Sadar > Dinajpur Sadar > Mithapukur > Modhukhali. Therefore, Durgapur and Modhukhali soil appeared as the most and least responsive to K fertilization, respectively (Figure 4). There was significant ($P < 0.001$) negative correlation ($R^2 = 0.70$, $r = -0.84$) between yield response to K fertilizer and soil initial K (Figure 6). The mean shoot dry matter yield in the 18 soils without K fertilization reduced drastically from 1st to 3rd crops, decreased slightly in the 4th to 5th crop due to climatic variation, and after that gradually declined up to the 7th crop. The differences in shoot dry matter yield between the K applied soils and the no added K fertilizer soils were gradually increased with the successive cropping (Figure 5).

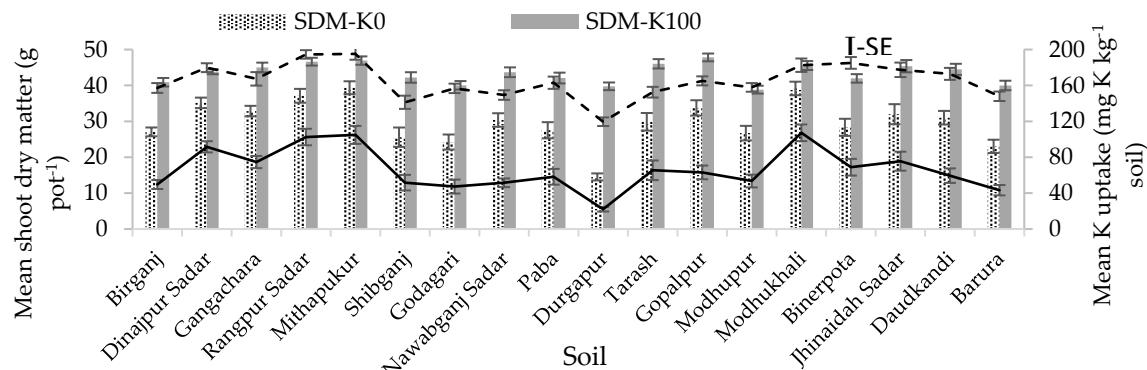


Figure 4. Trends for mean shoot dry matter (SDM) and mean K uptake over successive seven rabi maize crops in pots with K0 and K100 for 18 diverse soils of Bangladesh.

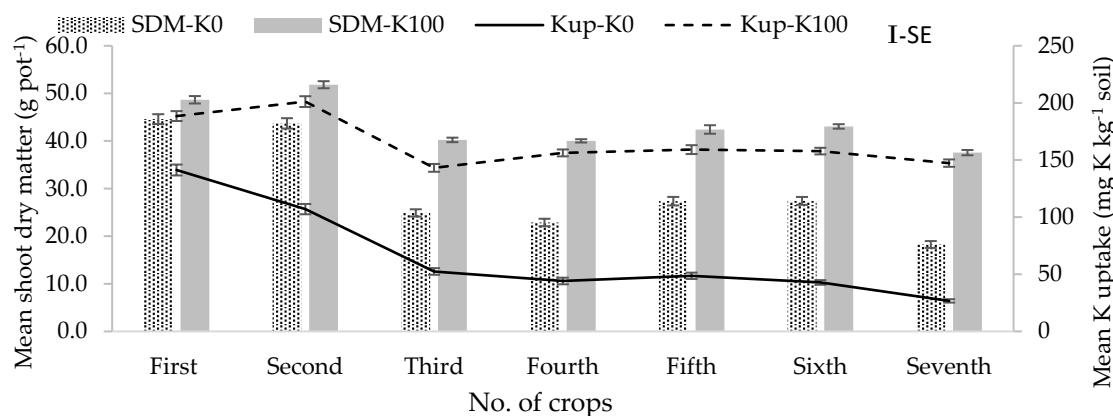


Figure 5. Trends for mean shoot dry matter (SDM) and mean K uptake over 18 diverse soils for seven successive cropping of rabi maize with K0 and K100 in pots in Gazipur, Bangladesh.

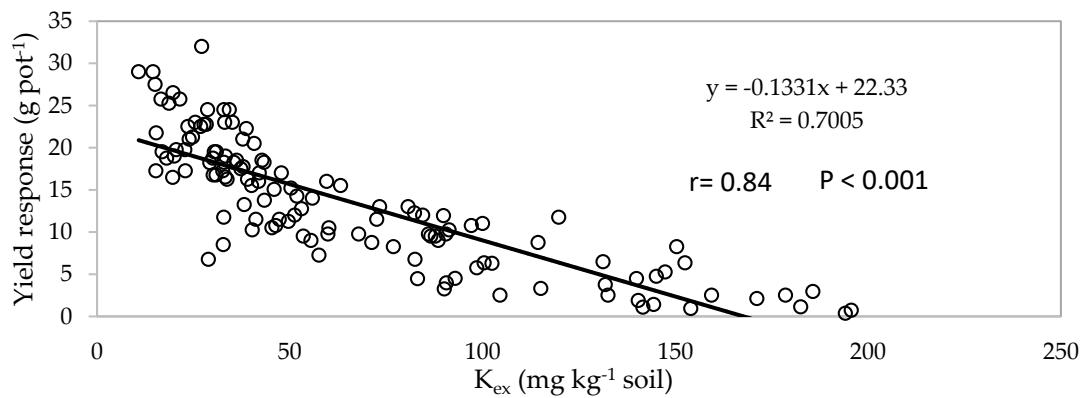


Figure 6. The relationship between initial soil Kex of 18 diverse soil of Bangladesh and yield response of maize grown up to V10-V12 for seven successive crops to K fertilizer in pot experiment, Gazipur, Bangladesh.

3.1.2 Soil K supplying capacity and K depletion over successive cropping

The amount of total K uptake by plants in different soils without application of K fertilizer was defined as the potential K-supplying capacity. The K uptake varied significantly due to the variation of soil K reserves among the soils. In control pots, average K uptake over seven successive crops varied from 22.1 to 107.3 mg kg⁻¹ soil (Figure 4). The lowest K uptake was found in Durgapur and significantly higher K uptake was recorded in Modhukhali and Mithapukur soils. In general, potential K-supplying capacity of these tested soils followed the order: Modhukhali > Mithapukur > Rangpur Sadar > Dinajpur Sadar > Jhinaidah Sadr > Gangachara > Binerpota > Tarash > Gopalpur > Daudkandi > Paba > Modhupur Nawabganj > Shibganj > Birganj > Godagari > Barura > Durgapur (Figure 4). Though the trends were similar for both +K and -K soils but the K uptake was 2-3 times higher for K-treated soils than the non-treated ones (Figure 4). In control pots mean K uptake over 18 soils drastically reduced from first to the third crop but it was gradually declined from fourth to seventh crops (Figure 5). There was a strong positive relationship in both soil Kex ($R^2 = 0.56-0.84$) and K_{nx} ($R^2 = 0.48-0.63$) with K uptake, but it was stronger in soil Kex than K_{nx} . Moreover, the relationship became gradually stronger with increasing the number of successive cropping (Figure 7). And soil Kex and K_{nx} decreased remarkably in control pots due to the growing of seven successive maize crops (Table 4).

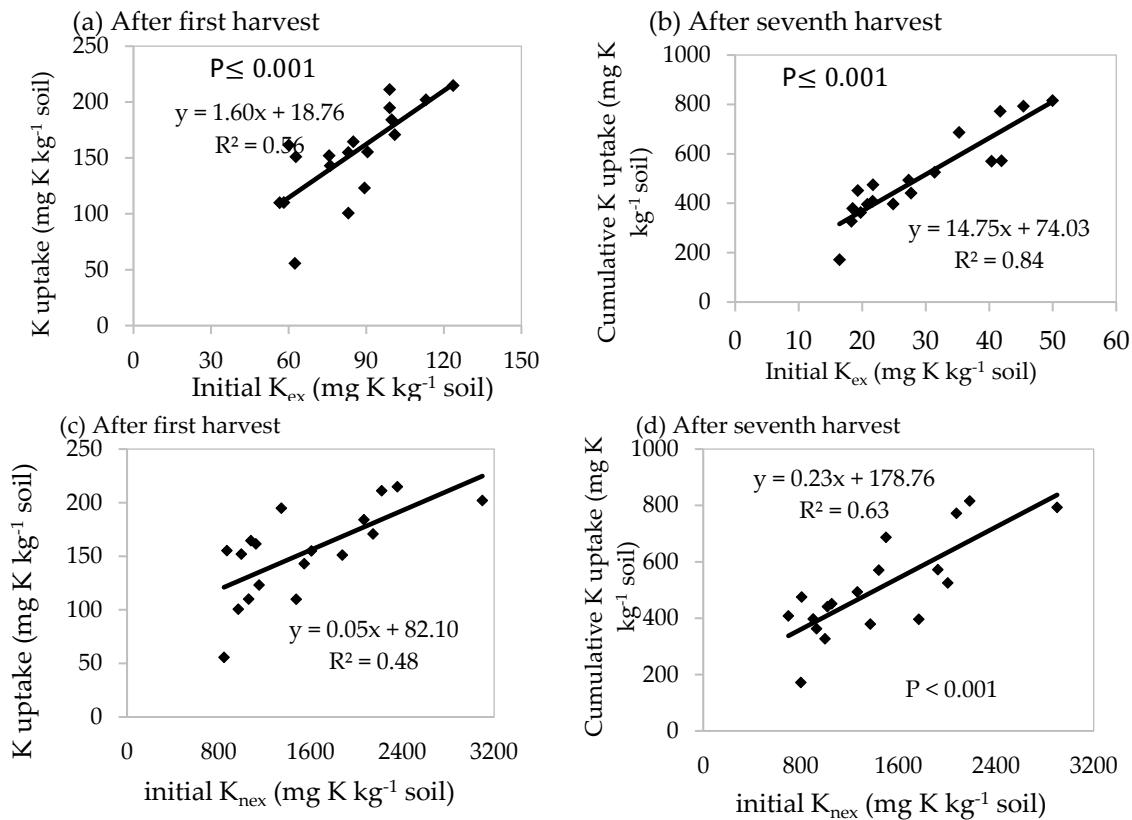


Figure 7. The relationship between initial K_{ex} and K uptake after first (a) and seventh (b), and between initial K_{nex} and K uptake after first (c) and seventh (d) *rabi* maize crops in pots.

Table 4. Amount of exchangeable and non-exchangeable K before the start of the experiment (initial) and after seven harvests (grown up to V10-V12) of *rabi* maize grown in pots with K0 and K100 with 18 diverse soils, Gazipur, Bangladesh.

Location of soil	Pre K_{ex}		Post K_{ex}		Pre K_{nex}		Post- K_{nex}	
Birganj	57	16	39	1475	1369	1435		
Dinajpur Sadar	83	37	66	1608	1498	1568		
Gangachara	76	35	57	1544	1439	1502		
Rangpur Sadar	99	36	76	2220	2075	2168		
Mithapukur	113	39	85	3098	2900	3028		
Shibganj	63	14	42	1876	1767	1849		
Godagari	76	18	50	996	928	971		
Nawabganj	83	20	68	970	901	944		
Paba	85	23	64	1080	1018	1061		
Durgapur	62	20	40	845	800	831		
Tarash	99	21	67	1345	1264	1322		
Gopalpur	90	20	55	871	807	846		
Modhupur	89	21	67	761	698	733		
Modhukhali	124	45	113	2357	2184	2360		
Binerpota	101	31	83	2145	2005	2102		
Jhinaidah Sadar	100	35	78	2065	1923	2016		
Daudkandi	60	18	37	1123	1053	1104		
Barura	58	14	37	1060	998	1045		

3.2 Field Experiment

The ANOVA for the means for all yield and yield attributing characters (except number of cobs plant¹) in all the farmers' fields across the three districts showed highly significant effects between the treatments ($P \leq 0.001$) due to farmers' fields being scattered over a large area with variable soils and land types. There was no significant effect ($P \geq 0.05$) on the interaction among the same treatment of different farmers for most of the measurable variables (except yield increase over control) in the same location due to less variability of soils and maintaining same practices for all farmers.

3.2.1 Growth and yield components

3.2.1.1 Plant height

Plant heights were 237 ± 1.35 , 186 ± 5.10 and 237 ± 3.51 cm in Rangpur, Rajshahi, and Comilla, respectively, while it was 217 ± 3.20 cm over all sites (Table 5). In all sites, significantly shortest plants were found in control plots, and the height increased progressively, though not significantly, with an increase of K rate up to 120 kg K ha^{-1} . In Rangpur and Rajshahi significantly taller plants were found with all K-treated plots except 40 kg K ha^{-1} plots, with slightly taller plants in MCM and NEM plots. In Comilla, however, maize plants in all K-treated plots were significantly taller than in the control plots.

3.2.1.2 Yield components

Cob length varied from 15.0 to 17.8 cm overall sites, ranging from $17.0-20.1$, $12.6-15.1$ and $15.4-19.3$ cm in Rangpur, Rajshahi, and Comilla, respectively (Table 5). Cob length increased progressively with increase of K fertilizer rate up to 120 kg ha^{-1} . In all locations, cobs were significantly longer for all levels of K and MCM- and NEM-based recommendations than in control. The longest cob was found with 120 kg K ha^{-1} plots in Rangpur and MCM-based fertilizer recommendation (88 kg K ha^{-1}) in Rajshahi, though it was statically identical with the NEM-based recommendation in all locations (Table 5).

The cob girth was 16.5 ± 0.27 , 14.78 ± 0.10 and 15.6 ± 0.22 cm in Rangpur, Rajshahi, and Comilla, respectively (Table 5). Cob girth increased progressively with the increase of K rates up to 120 kg K ha^{-1} . Cob girth in control plots was lower than other treatments in all sites though it was only statistically lower to 120 and 160 kg K ha^{-1} treated plots in Rangpur. The highest cob girth for 120 kg K ha^{-1} was found in Rangpur and Rajshahi and in NE fertilizer recommended plots in Comilla, though it was statically identical to the MCM fertilizer recommended plots in all locations. In Rajshahi and Comilla, except control, all treatments were statistically identical.

The number of grains cob^{-1} was 495 ± 9.82 , 367 ± 3.09 and 442 ± 17.05 in Rangpur, Rajshahi, and Comilla, respectively. The number of grains cob^{-1} increased progressively with the increase of K rate up to 120 kg ha^{-1} . It was the highest for the NEM-based recommendation in Rangpur and Comilla, 160 kg K ha^{-1} treated plots in Rajshahi, though it was statistically identical to all K levels and MCM- and NEM-based fertilizer recommendations (Table 5).

The weight of 1000-grains varied significantly among the treatments, ranging 314 ± 7.03 , 3121 ± 8.61 and 307 ± 3.68 g in Rangpur, Rajshahi, and Comilla, respectively. Across the sites, it varied significantly ($P < 0.001$) from 252 g in K0 to 339 g in NEM based recommendation plot. The results showed that NEM-based fertilizer recommendation resulted in heaviest grains in all locations, followed by all levels of K and MCM-based recommendation (Table 5).

Table 5. Effect of K fertilization on growth, and yield and yield attributes of *rabi* maize in three field experimental sites in Bangladesh, 2012-13.

Treatment (kg K ha ⁻¹)	Plant height (cm)	Cob length (cm)	Cob girth (cm)	Cob s plan t ⁻¹	Grain s cob ⁻¹	1000-grain wt. (g)	Grain yield (t ha ⁻¹)	Biomass (t ha ⁻¹)	HI	Yield response (%)
Rangpur										
0	218c	17.0b	15.4b	0.99	432b	248d	6.35c	12.92c	0.49a	-
40	227b	18.0ab	16.2a	1.00	481a	303c	7.51c	15.19c	0.49a	17.72d
80	228a	19.2ab	16.4a	1.00	495a	312bc	9.82ab	19.71a	0.50a	52.08bc
120	231a	20.1a	17.5a	1.00	518a	343a	10.21a	20.70a	0.49a	60.51a
160	228a	19.5ab	17.3a	1.00	494a	308bc	9.04b	18.20b	0.50a	40.55c
MCM	233a	19.6ab	16.3a	1.00	516a	339ab	10.38a	21.01a	0.49a	62.76ab
NE (117)	231a	19.8ab	16.9a	1.01	527a	345a	10.95a	21.98a	0.50a	70.47a
Mean	228	19	16.5	1	495	314	9.18	18.53	0.5	50.68
SE (±)	1.35	0.44	0.27	0.00	9.82	7.03	0.33	0.67	0.001	4.12
Rajshahi										
0	147c	12.6e	13.7c	0.99	343c	228d	5.42c	10.80d	0.50ab	-
40	172b	13.7d	14.6b	0.99	368a	310c	6.49b	13.17c	0.49bc	22.01c
80	184a	13.8cd	14.8a	0.99	365a	347ab	8.09a	16.40a	0.49bc	51.84ab
120	203a	14.5b	15.2a	0.99	361b	335ab	8.63a	17.16a	0.50ab	58.75a
160	196a	14.2bc	15.1a	1.00	380a	321bc	8.02a	15.51b	0.52a	43.49b
MCM	204a	15.1a	15.1a	0.99	379a	357a	8.41a	17.23a	0.49c	59.33a
NE (103)	198a	14.4bc	15.0a	1.00	376a	349a	8.66a	17.02a	0.51ab	57.49a
Mean	186	14.01	14.78	1.00	367.4	321.1	7.67	15.32	0.50	48.82
SE (±)	5.1	0.16	0.1	0.00	3.09	8.61	0.25	0.49	0.002	3.94
Comilla										
0	208b	15.4b	13.5b	0.99	316b	280d	4.86b	9.70c	0.50a	-
40	232a	17.4ab	15.3a	1.00	447a	297cd	5.65b	11.59b	0.49b	20.57b
80	244a	18.6a	15.9a	0.99	431a	301bc	6.95a	13.70a	0.51a	40.79a
120	245a	19.3a	16.1a	1.00	470a	310ab	7.45a	14.85a	0.50a	54.02a
160	244a	19.1a	16.1a	0.99	468a	319ab	6.93a	13.91a	0.50ab	44.29a
MCM	244a	18.9a	15.9a	1.00	473a	316ab	7.01a	14.03a	0.50a	44.00a
NE (100)	243a	18.9a	16.2a	1.00	488a	324a	7.38a	14.46a	0.51a	49.80a
Mean	237	18.2	15.6	1.00	442	307	6.60	13.18	0.50	42.24
SE (±)	3.51	0.32	0.22	0.00	17.05	3.68	0.26	0.52	0.002	2.9
All sites (Mean)										
0	191c	15.0c	14.2c	1.00	364b	252d	5.54d	11.14d	0.50ab	-
40	210b	16.4b	15.3b	1.00	432a	303c	6.55c	13.32c	0.49c	20.10d
80	219a	17.2ab	15.7a	1.01	430a	320b	8.28ab	16.60a	0.50ab	48.24bc
120	226a	18.0a	16.3a	1.00	450a	329ab	8.76ab	17.57a	0.50ab	57.76a
160	223a	17.6ab	16.2a	1.00	447a	316bc	7.99b	15.87b	0.50a	42.78c
MCM	227a	17.8a	15.8a	1.00	456a	338a	8.60ab	17.42a	0.49bc	55.36ab
NE (106)	224a	17.7a	16.0a	1.00	464a	339a	8.99a	17.82a	0.51a	59.25a
Mean	217	17.1	15.6	1.00	435	314	7.82	15.68	0.50	47.25
SE (±)	3.2	0.31	0.14	0.00	8.71	3.91	0.2	0.400	0.001	1.85

Data not sharing the same letter(s) in a column are significantly different according to Duncan's New Multiple-Range Test at 5% level of probability (Steel et al., 1997), *MCM- Site-Specific Nutrient Management through "Maize Crop Manager" developed by IRRI, NE- Site-Specific Nutrient Management through "Nutrient Expert" for maize developed by IPNI, SE-Standard error of mean.

3.2.1.3 Yield and yield response

The average grain yields across all treatments were 9.18 ± 0.33 , 7.67 ± 0.25 and $6.60 \pm 0.26 \text{ t ha}^{-1}$ in Rangpur, Rajshahi, and Comilla, respectively. Likewise, average biomass was 18.53 ± 0.67 , 15.32 ± 0.49 and $13.18 \pm 0.52 \text{ t ha}^{-1}$, respectively, in the three districts. The average grain and biomass yields over all districts were 7.82 ± 0.20 and 15.68 ± 0.40 , respectively (Table 5). Grain and biomass yields progressively increased with the increase of K rate up to 120 kg K ha^{-1} . Grain and biomass yields in control plots were significantly lower compared to other treatments in Rajshahi, but it was similar to 40 kg K ha^{-1} plots in Rangpur and Comilla. In all districts, grain and biomass yields were significantly similar for 80 , 120 , 160 kg K ha^{-1} , and NEM- and MCM-based fertilizer recommendation. harvest index varied from 0.49 to 0.50 , 0.49 to 0.52 , and 0.49 to 0.51 in Rangpur, Rajshahi and Comilla, respectively. It varied significantly across treatments in Rajshahi and Comilla, but not in Rangpur. Yield response to K application across treatments varied from 17.72 to 70.47% , 22.01 to 59.33 , and 20.57 to 54.02% in Rangpur, Rajshahi, and Comilla, respectively, and when averaged across sites, it varied from 20.10 to 59.25% (Table 5).

3.2.2 Estimation of K supplying capacity

The average K concentration in maize grain over treatments were 0.439 ± 0.013 , 0.439 ± 0.012 and $0.409 \pm 0.014\%$ in Rangpur, Rajshahi, and Comilla, respectively. Likewise, average K concentration in maize stover were 1.32 ± 0.05 , 1.21 ± 0.06 and $1.24 \pm 0.05\%$, respectively, in the three districts. The average K concentration in grain and biomass yields over all districts were 0.429 ± 0.008 and 1.24 ± 0.03 , respectively (Table 6). K concentration in maize grain and stover over sites varied from 0.309 to 0.520% and from 0.88 to 1.73% , respectively. K concentration in maize grain and stover progressively increased with the increase in K rate up to the maximum dose (160 kg K ha^{-1}). K concentration across locations and treatments was lowest (0.31% in grain and 0.88% in stover) in control plots and highest in 160 kg K ha^{-1} plots (0.52% in grain and 1.73% in stover) (Table 6).

The total mean K uptake by maize (grain+stover) across treatments was from 166 ± 9.66 , 128 ± 7.39 , and $106 \pm 6.40 \text{ kg ha}^{-1}$ in Rangpur, Rajshahi, and Comilla, respectively. Total K uptake over the sites varied significantly from 67.1 to $178.3 \text{ kg K ha}^{-1}$. Total K uptake progressively increased with the increase in K rate up to 160 kg K ha^{-1} . Total K uptake by maize across treatments and locations was lowest in control plots and highest in 160 kg K ha^{-1} . Across all locations, in both control and K-treated plots, the total K uptake, i.e., the K-supplying capacity of soils, was in the order: Rangpur > Rajshahi > Comilla, and this was similar to the results found in the pot study (Table 6). There was a strong positive linear relationship ($R^2 = 0.73$, $P < 0.001$) between indigenous soil K to K uptake in without K fertilized plots (Figure 8a), but no such relationship with indigenous soil K was observed in high K fertilized plots (Figure 8b).

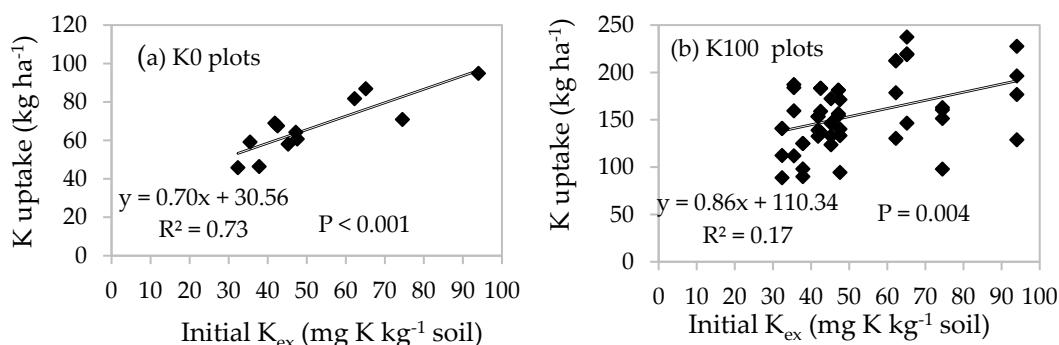


Figure 8. The relationship between initial soil K_{ex} and K uptake in (a) control plots, K0 ($n=12$) and (b) K-fertilizer applied plots, K100 ($n=48$) in three field experimental sites in Bangladesh

Table 6. Effect of K fertilization on K content and K uptake, and agronomic and recovery efficiency of K by *rabi* maize in three field experimental sites in Bangladesh, 2012-13.

Treatment (kg K ha ⁻¹)	K concentration (%)		K uptake (kg ha ⁻¹)			AE _K	RE _K
	Grain	Stover	Grain	Stover	Total		
Rangpur							
0	0.312d	0.97c	19.8c	63.8c	83.6c	-	-
40	0.404c	1.21d	30.4b	93.4c	123.8b	29.05b	1.01a
80	0.447b	1.25bc	44.1a	124.7b	168.8a	43.41a	1.06a
120	0.455b	1.43b	46.6a	150.3ab	196.9a	32.19b	0.94a
160	0.527a	1.73a	47.6a	159.6a	207.2a	16.80c	0.77a
MCM (88)	0.452b	1.29bc	47.0a	137.4ab	184.4a	46.10a	1.15a
NE (117)	0.476b	1.37bc	52.2a	151.9ab	204.1a	39.57ab	1.04a
Mean	0.439	1.32	41.1	125.87	166.97	34.52	1.00
SE (±)	0.013	0.05	2.3	7.49	9.66	2.44	0.06
Rajshahi							
0	0.317d	0.81f	17.2d	43.4e	60.5f	-	-
40	0.396c	0.99e	25.7c	66.0d	91.7e	26.58a	0.78ab
80	0.441b	1.11d	35.7b	92.2c	127.9d	33.30a	0.84ab
120	0.479b	1.33b	41.2a	114.1b	155.3b	26.73a	0.79ab
160	0.519a	1.82a	41.4a	135.7a	177.2a	16.20b	0.73b
MCM (88)	0.466b	1.23bc	39.3ab	107.9b	147.2bc	34.20a	1.00a
NE (103)	0.456b	1.19cd	39.4ab	99.0bc	138.4cd	32.37a	0.79ab
Mean	0.439	1.21	34.3	94.0	128.3	28.23	0.82
SE (±)	0.012	0.06	1.75	5.76	7.39	1.49	0.03
Comilla							
0	0.299d	0.88d	14.5c	42.7d	57.2d	-	-
40	0.356cd	1.04c	20.1bc	61.5cd	81.7cd	19.62ab	0.61a
80	0.419b	1.15bc	29.4ab	77.3bc	106.6bc	26.02a	0.62a
120	0.447b	1.24b	33.6a	91.8b	125.4ab	21.57ab	0.57a
160	0.516a	1.65a	35.8a	114.8a	150.6a	12.90b	0.58a
MCM (88)	0.430b	1.18bc	30.7a	83.0b	113.6b	23.93a	0.64a
NE (100)	0.394bc	1.11bc	29.0ab	77.9bc	106.9bc	25.10a	0.50a
Mean	0.409	1.177	27.59	78.4	106	21.52	0.59
SE (±)	0.014	0.045	1.77	4.74	6.4	1.47	0.02
Across sites							
0	0.309d	0.88e	17.2c	49.9e	67.1e	-	-
40	0.385c	1.08d	25.4b	73.7d	99.0d	25.09b	0.80ab
80	0.436b	1.17c	36.4a	98.0c	134.4c	34.25a	0.84ab
120	0.460b	1.33b	40.5a	118.7b	159.2b	26.83b	0.77ab
160	0.520a	1.73a	41.6a	136.7a	178.3a	15.30c	0.70b
MCM (88)	0.449b	1.23c	39.0a	109.4bc	148.4bc	34.74a	0.93a
NE (106)	0.442b	1.22c	40.2a	109.6bc	149.8bc	32.35a	0.78ab

Data not sharing the same letter(s) in a column are significantly different according to Duncan's New Multiple-Range Test at 5% level of probability (Steel et al., 1997), *MCM- Site-specific nutrient management through "Maize Crop Manager" developed by IRRI, #NE- Site-specific nutrient management through "Nutrient Expert" for maize developed by IPNI, SE-Standard error of mean.

3.2.4 K-use efficiency

There was a significant effect of K application on agronomic efficiency (AE_K) and recovery efficiency (RE_K) in each site and across all sites. The AE_K varied significantly over control from 16.8 to 46.1, 16.2 to 34.2, and 12.9 to 26.0 in Rangpur, Rajshahi, and Comilla, respectively. Likewise, the ranges of RE_K were from 0.77 to 1.15, 0.73 to 1.00, and 0.50 to 0.64, respectively in the three sites. AE_K

and RE_K over the sites varied from 15.30 to 34.74 and 0.70 to 0.93, respectively, and decreased progressively with increase of K rates (Table 6). Both AE_K and RE_K were lowest for the highest K dose (160 kg ha^{-1}) compared to other rates. Though not significantly different, the MCM-based recommendation generally resulted in higher AE_K and RE_K than NEM-based recommendation (Table 6)

4. Discussion

Until a few years back, there was a general perception that agricultural soils in South and South East Asia, including those in Bangladesh, are well supplied with K, and hence there was no need to apply K fertilizer to crops. But recently, many investigations, reviews and research results have shown that the intensification of agriculture in the region with little or no K application caused gradual K mining, and crop responses to K are observed in many of those countries including Bangladesh [37]. Such results suggest the need for application of K fertilizers for sustaining or increasing the crop yields. Proper application and management of K require a thorough understanding of soil K dynamics and its uptake by crops at various K inputs and outputs scenarios and for different cropping systems. It is well known that the K availability to the plants does not only depend on the size of the available K pool in the soil but also on the other K pools and their K release patterns, and its transport from soil solution to the root zone for its uptake by plants [38]. It is hypothesized that soils differ in terms of mineralogy, soil K reserves, K-supplying capacity and allowable drawdown. Thus, some soils would require more while others would require less K to grow profitable maize crops [39].

Plant available K can be assessed either by plant growth analysis or by simple chemical extraction method or by a combination of both procedures with plants grown in no-K added plots. A robust relationship ($R^2=0.82$) between K uptake and grain yield was observed in no-K plots, which was considered as a good measure of soil K supply to crops [40]. When assessed by plant K uptake, it can be termed as "K-supplying capacity" whereas if assessed by extracting the soil with one or more extractions, a chemical index of available K (K-releasing capacity), can be the true index of plant available K. Consequently, many investigators reported, while "plant available K" can be equated to the K-supplying capacity of the soil, it can only be related to the K-releasing capacity. Thus, both K-releasing and K-supplying capacity can be considered the measures of the ability of a soil to supply K to plants [41–43]. The amount of total K uptake by plants from a soil depends on the potential of K-supplying capacity.

The K depletion pattern in this study was carried out in a pot experiment with the successive planting of maize for seven harvests to understand K-supplying capacity from soil reserves of major soils in Bangladesh. The 18 tested soils varied considerably in supporting K uptake over seven crops, ranging from 22.1 – $103.7 \text{ mg K kg}^{-1}$ soil, and the uptake in control pots was lowest in Durgapur (Rajshahi), and highest in Mithapukur and Modhukhali (Rangpur) soils. Similar trends were observed for K-treated pots with K uptake ranging from 119.6 to $195.14 \text{ mg K kg}^{-1}$. The results from this study assisted us to divide the potential K-supplying capacity of 18 soils into three categories: low, medium, and high, and corresponding to average K uptake over seven successive crops of <50 , 51 – 80 and $>80 \text{ mg K kg}^{-1}$ soil, respectively (Figure 4). According to the classification, among the tested soils, K uptake (or soil K-supply capacity) by maize was low in Durgapur, Barura, Godagari and

Birganj; medium in Nawabganj, Shibganj, Modhupur, Paba, Daudkandi, Gopalpur Tarash, Binerpota, Gangachara and Jhinaidah soils; and high in Dinajpur Sadar, Rangpur Sadar, Mithapukur and Modhukhali soils (Figure 4). In line to our study, similar observations were also recorded in Guinea grass for six successive crop harvests. In that study, the tissue K concentration and K uptake in plants, and soil K-supplying capacity varied widely in various soils and was higher for K-treated than for no K-applied soils [44–46].

In the multi-location field experiment, growth and yield attributing characteristics of maize, except number of cobs per plant, responded to K fertilization significantly in all locations. Yield increase over control varied 18–79%, 22–59% and 21–54% in Rangpur, Rajshahi and Comilla, respectively [47]. In all locations, significantly higher grain yield was found with NEM-based fertilizer recommendation followed respectively by MCM-based recommendation, 120, 80 and 160 kg K ha^{-1} , and lowest with no K added and 40 kg K ha^{-1} treatments. Both NEM- and MCM-based recommendations were based on the SSNM principles which considered previous crop's residues and manures and fertilizers practices, and indigenous soil fertility [27]. Previous results have also shown that the MCM and NEM have great potential to estimate K fertilizer recommendation for maize, which could help to reduce the cost of production and to increase yield and profit by reducing the over or underuse of fertilizer to the crop [26,39].

K uptake by maize was governed by K content in plant tissue and above ground dry matter. The K concentration of the plant tissue was consistent with the K availability in the soil. Therefore, K uptake by maize in K-omission plots can be a reliable measure of K-supplying capacity of soil [41,42,48]. In control plots, K uptake by maize varied from 57.2 to 83.6 kg ha^{-1} . The order of K-supplying capacity in the field experiment was Rangpur > Rajshahi > Comilla which was similar to the order observed in the pot study. The correlation between K uptake by maize at harvest and initial K_{ex} and K_{nex} were positive and linear. Plots of cumulative K uptake by maize from 1st to 7th harvest versus initial K_{ex} contents showed a progressively higher utilization of NH₄OAc-K by maize during the experiment (Figure 7 a & b). Moreover, the highly significant R^2 values (0.56 to 0.84) revealed that 56 to 84% of the K uptake by maize was governed by the initial K_{ex} content. However, the slope (>1) of the linear regression line indicated that the initial K_{ex} was not sufficient to meet the entire uptake requirement of maize starting from the 1st crop to the 7th crop. The value of slope (1.6 to 14.8) increased with increase in crop number revealing the gradual depletion in K_{ex} pool and therefore, the uptake of K might have been complimented from other soil K pools also (Figure 7 a & b). In the case of K_{nex} , the lower value of the slope and R^2 of a linear relationship for the 1st harvest indicated that the contribution of the K_{nex} pool to K uptake by maize was lower than the K_{ex} pool. But the relationship of cumulative K uptake versus K_{nex} at 7th harvest became stronger with a higher value of slope than the 1st harvest. The value of slope and R^2 increased with successive crops indicating that the K uptake dependency on the K_{nex} pools was increased due to reduced K_{ex} availability in the soil with successive exhaustive cropping in control pots (Figure 7 c & d). A significant contribution of K_{nex} to crop uptake was reported in other studies also. However, K_{nex} is not measured in routine soil K test in most countries and the depletion of K_{nex} often remain unnoticed to the detriment of soil K fertility.

The amount of K uptake by maize in the K-applied plots was significantly higher than in control plots and ranged from 99 to 178.3 kg K ha^{-1} across the sites. The highest K uptake occurred with 160 kg K ha^{-1} , though 88 kg K ha^{-1} resulted in significantly higher agronomic and recovery efficiency of K. The K requirements vary for different crops, varieties, and locations in which they are grown [49]. Other studies have also shown that crop K requirement depends on the K status and K dynamics in soils, as well as efficient K use, which depends also on the rooting pattern of different crops and varieties, and their productivity. There is thus essential need for K to be supplied at an optimum dose

and maintained to augment production and ensure to improve quality crop [49]. Nevertheless, both the concomitant increase in yield and efficiency improvement with added K are important considerations for improved K management. Finally, improving nutrient use efficiency should not be the singular goal of any sustainable nutrient management program as higher efficiencies can be achieved by less and less nutrient application. In this study, the trend is yield and efficiency increase from 40 to 80 kg K, but efficiencies drop as 120 or 160 kg of K are applied, clearly suggesting that yield improvement at these rates are not enough to improve use efficiencies also. In any improved K management programs, decision support system (DSS) tools such as MCM or NEM strategies could be the better options for improved K fertilizer management, as the current study showed that, these strategies increased K application but also increased maize yield to keep the efficiencies at higher levels. SSNM strategies, such as MCM and NEM DSS tools, can take care of adequate and balanced application of all nutrients, including K, and hence their adoption in Bangladesh and South Asia would be important not just for K management but for the management of all nutrients.

5. Conclusions

In pot study, maize responded to added K in Godagari, Durgapur, and Modhupur soils out of 18 soils from the first crop and 50% soils responding from the second crop, with remaining soils responding from the third crop onwards. The mean yield response over seven successive crops across 18 soils varied from 20 to 195%, where least and most responsive soils to K fertilizer were found in Modhukhali and Durgapur soils. In control pots, K-supplying capacity over seven successive crops varied (22.1-107.3 mg K kg soil⁻¹) significantly and there was a significant ($P<0.001$) negative correlation between yield response and indigenous K-supplying capacity. In the field validation experiment, yield and yield attributes of maize responded to K fertilizer significantly in all locations. Potassium fertilizer increased grain yield from 18 to 79%.

The current research established that the requirement of K was 111-122 kg K ha⁻¹ for maize cultivation in Bangladesh. Total K uptake by the plot that did not receive K fertilizer in on-farm trials, considered as K-supplying capacity of the soils, was in the order: Rangpur> Rajshahi> Comilla, which was similar to the results of pot study. Thus, assessment of K-supplying capacity of major soils in Bangladesh will be useful for managing K fertility in soils and K nutrition for maize. The study provides evidence of the essentiality of adequate and balanced K application in maize in Bangladesh for sustainably improving or maintaining high yields. The results, however, have great implications for South Asia as a whole as maize is replacing rice and wheat in vast areas of the region because of its economic value and climate resilience. Further studies would be required to better understand K-supplying capacity, and yield and K-use efficiency of maize in more diverse soils across maize-growing areas of South Asia.

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References

1. Shiferaw, B.; Prasanna, B. M.; Hellin, J.; Bänziger, M. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Secur.* **2011**, *3*, 307–327, doi:10.1007/s12571-011-0140-5.
2. Gerland, P.; Raftery, A. E.; Ševčíková, H.; Li, N.; Gu, D.; Spoorenberg, T.; Alkema, L.; Fosdick, B. K.; Chunn, J.; Lalic, N.; Bay, G.; Buettner, T.; Heilig, G. K.; Wilmoth, J. World population stabilization unlikely this century. *Science* (80-.). **2014**, *346*, 234–237, doi:10.1126/science.1257469.
3. WB *World Development Indicators 2014*. World Bank, Washington DC.; 2014;
4. DAE *Krishi Diary*; Agricultural Information Services, Ministry of Agriculture, Khamar Bari: Dhaka, 2018;
5. Sanley A. Barber Potassium availability at the soil-root interface and factors influencing potassium uptake. In *Potassium in Agriculture*; RD, M., Ed.; American Society of Agronomy, Madison, United States of America, 1985; p. 309–324.
6. Dobermann, A.; Cassman, K. G.; Mamaril, C. P.; Sheehy, J. E. Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. *F. Crop. Res.* **1998**, *56*, 113–138, doi:10.1016/S0378-4290(97)00124-X.
7. Regmi, A. P.; Ladha, J. K.; Pathak, H.; Pasuquin, E.; Bueno, C.; Dawe, D.; Hobbs, P. R.; Joshy, D.; Maskey, S. L.; Pandey, S. P. Yield and Soil Fertility Trends in a 20-Year Rice–Rice–Wheat Experiment in Nepal. *Soil Sci. Soc. Am. J.* **2002**, *66*, 857, doi:10.2136/sssaj2002.8570.
8. Srivastava, S.; Raghavareddy Rupa, T.; Swarup, A.; Singh, D. Effect of long-term fertilization and manuring on potassium release properties in a Typic Ustochrept. *J. Plant Nutr. Soil Sci.* **2002**, *165*, 352–356, doi:10.1002/1522-2624(200206)165:3<352::AID-JPLN352>3.0.CO;2-E.
9. Singh, B.; Singh, Y.; Imas, P.; Jian-chang, X. Potassium Nutrition of the Rice- Wheat Cropping System. *Adv. Agron.* **2001**, *81*, 203–259.
10. Timsina, J.; Jat, M. L.; Majumdar, K. Rice-maize systems of South Asia: Current status, future prospects and research priorities for nutrient management. *Plant Soil* **2010**, *335*, 65–82, doi:10.1007/s11104-010-0418-y.
11. Doboerman, A. and F. T. *Nutrient Disorders & Nutrient Management*; First.; Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC) and International and International Rice Institute (IRRI), 2000; ISBN 9810427425.
12. Ali, M. M.; Saheed, S. M.; Kubota, D.; Masunaga, T.; Wakatsuki, T. Soil degradation during

the period 1967–1995 in Bangladesh. *Soil Sci. Plant Nutr.* **1997**, *43*, 879–890, doi:10.1080/00380768.1997.10414654.

13. Saleque, M. A.; Saha, P. K.; Panaullah, G. M.; Bhuiyan, N. I. Response of wetland rice to potassium in farmers' fields of the Barind tract of Bangladesh. *J. Plant Nutr.* **1998**, *21*, 39–47, doi:10.1080/01904169809365381.

14. Majumdar, K.; Plant, I.; Asia, S. Improving nutrient management for sustainable intensification of maize. **2016**, *2*, 1–32.

15. Panaullah, G. M.; Timsina, J.; Saleque, M. A.; Ishaque, M.; Pathan, A. B. M. B. U.; Connor, D. J.; Saha, P. K.; Quayyum, M. A.; Humphreys, E.; Meisner, C. A. Nutrient uptake and apparent balances for rice-wheat sequences. III. Potassium. *J. Plant Nutr.* **2006**, *29*, 173–187, doi:10.1080/01904160500416554.

16. CD.C. Olk, K.G. Cassman, G. Simbahan, P.C. Sta. Cruz, 3, S. Abdulrachman, R. N.; Satawathananont, P. S. T. & S. Interpreting fertilizer-use efficiency in relation to soil nutrient-supplying capacity, factor productivity, and agronomic efficiency. *Nutr. Cycl. Agro-ecosystems* **1999**, *16*, 21, 35–41, doi:10.1023/A.

17. Cassman, K. G.; Dobermann, A. R.; Walters, D. T. Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. *Agron. Hortic.* **2002**, *31*, 132–140.

18. Dobermann, A. Nutrient use efficiency—measurement and management. In *IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium, 7–9 March 2007*; 2007; p. 28.

19. Liu, X.; He, P.; Jin, J.; Zhou, W.; Sulewski, G.; Phillips, S. Yield gaps, indigenous nutrient supply, and nutrient use efficiency of wheat in China. *Agron. J.* **2011**, *103*, 1452–1463, doi:10.2134/agronj2010.0476.

20. Sparks, D. L.; Page, A. L.; Helmke, P. A.; Loepert, R. A.; Soltanpour, P. N. Tabatabai, M. A.; Johnston, C. T.; Sumner, M. E. Methods of soil analysis: Chemical Methods. In *Chemical methods*; 1996; p. 1390 ISBN 0891188258.

21. ASTM Standard Test Method for Particle-Size Analysis of Soils. *Astm* **2007**, *D422-63*, 1–8, doi:West Conshohocken, PA.

22. Ritchie, S.; Hanway, J.; Benson, G. How a corn plant develops. *Sci. Technol.* **1989**, 1–25.

23. Jones, J. B.; Jr. Laboratory Guide for Conducting Soil Tests and Plant Analysis. In *Laboratory Guide for Conducting Soil Tests and Plant Analysis*; 2001; p. 202 ISBN 1420025295.

24. FAO-UNDP *Land Resources Appraisal of Bangladesh for Agricultural Development*; Rome, Italy, 1988; Vol. II;

25. Buresh, R. J.; Pampolino, M. F.; Witt, C. Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems. *Plant Soil* **2010**, *335*, 35–64, doi:10.1007/s11104-010-0441-z.

26. Satyanarayana, T.; Kaushik, M.; Biradar, D. P. New approaches and tools for site-specific nutrient management with reference to potassium. *Spec. Issue Potassium Nutr. enhancing yield Qual. Crop.* **2011**, *24*.

27. Anand, S. R.; Vishwanatha, J.; Rajkumar, R. H. Site Specific Nutrient Management (SSNM) Using “ Nutrient Expert ” for Hybrid Maize (Zea mays L .) Under Zero Tillage in Thungabhadra Project (TBP) Command Area of Karnataka. **2017**, *6*, 3597–3605.

28. Witt, C.; Found, M. G. A Site-Specific Nutrient Management Approach for Irrigated , Lowland Rice in Asia A Site-Specific Nutrient Management Approach for Irrigated , Lowland Rice in Asia. *Better Crop. Int.* **2016**, *16*, 20–24.

29. Witt, C.; Pasuquin, J.-M.; Dobermann, a Site-Specific Nutrient Management for Maize in Favorable Tropical Environments of Asia. *5th Int. Crop Sci. Congr.* **2008**.

30. Xu, X.; He, P.; Qiu, S.; Pampolino, M. F.; Zhao, S.; Johnston, A. M.; Zhou, W. Estimating a new approach of fertilizer recommendation across small-holder farms in China. *F. Crop. Res.* **2014**, *163*, 10–17, doi:10.1016/j.fcr.2014.04.014.

31. Dobermann, A.; Witt, C.; Abdulrachman, S.; Gines, H. C.; Nagarajan, R.; Son, T. T.; Tan, P. S.; Wang, G. H.; Chien, N. V.; Thoa, V. T. K.; Phung, C. V.; Stalin, P.; Muthukrishnan, P.; Ravi, V.; Babu, M.; Simbahan, G. C.; Adviento, M. A. A.; Bartolome, V. Estimating indigenous nutrient supplies for site-specific nutrient management in irrigated rice. *Agron. J.* **2003**, *95*, 924–935, doi:10.2134/agronj2003.0924.

32. Xu X He P Pampolino M Johnston A Qiu S Zhao S Chuan L Zhou W Fertilizer recommendation for maize in China based on yield response and agronomic efficiency. *F. Crop. Res.* **2014**, *157*, 27–34.

33. James H Cock, K. a G. Laboratory Manual for Physiological Studies of Rice. *Dspaceirriorg* **1976**, 69–72, doi:10.1007/978-3-642-22067-8_9.

34. R Development Core Team, R. R software. *R Found. Stat. Comput.* **2008**, *739*, 409.

35. Chambers, J. M. *Software for Data Analysis Programming with R*; 2008; Vol. 15; ISBN 9780387759357.

36. Steel, Robert G. D. (Robert George Douglas) & Dickey, David A & Torrie, J. H. (James H. *Principles and procedures of statistics : a biometrical approach*; 3rd ed.; McGraw-Hill: New York, 1997;

37. A. Dobermann, P. C. Sta. CruzK, G. C. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. I. Potassium uptake and K balance. **1996**, *46*, 1–10.

38. Barber, S. A. *Soil Nutrient Bioavailability: A Mechanistic Approach*; 2nd ed.; John Wiley and Sons: New York, 1995; ISBN 978-0-471-58747-7.

39. Timsina, J.; Kumar Singh, V.; Majumdar, K. Potassium management in rice-maize systems in South Asia. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 317–330.

40. Pathak, D. S.; Aggarwal, P. K.; Rötter, R. P.; Kalra, N.; Bandyopadhyaya, S. K.; Prasad, S.; van keulen, H. *Modelling the quantitative evaluation of soil nutrient supply, nutrient use efficiency, and fertilizer requirements of wheat in India*; 2003; Vol. 65;

41. Fergus, I. F.; Martin, A. E. Studies on potassium. IV. Interspecific differences in the uptake of

non-exchangeable potassium. *Soil Res.* **1974**, *12*, 147–158.

42. Memon, Y. M.; Fergus, I. F.; Hughes, J. D.; Page, D. W. Utilization of non-exchangeable soil potassium in relation to soil type, plant species and stage of growth. *Soil Res.* **1988**, *26*, 489–496.

43. A. Surapaneni , R.W. Tillman , J.H. Kirkman, P. E. H. G. & A. H. C. R. Potassium-supplying power of selected Pallic soils of New Zealand 1 . Pot trial study Potassium - supplying power of selected Pallic soils of New Zealand. **2002**, doi:10.1080/00288233.2002.9513501.

44. Darunsontaya, T.; Suddhiprakarn, A.; Kheoruenromne, I.; Prakongkep, N.; Gilkes, R. *The forms and availability to plants of soil potassium as related to mineralogy for upland Oxisols and Ultisols from Thailand*; 2012; Vol. 170;.

45. Hussain, A.; Arshad, M.; Ahmad, Z.; Ahmad, H. T.; Afzal, M.; Ahmad, M. Potassium Fertilization and Maize Physiology Potassium Fertilization Influences Growth, Physiology and Nutrients Uptake of Maize (*Zea Mays L.*). *Cercet. Agron. în Mold.* **2015**, *XLVIII*, 37–50.

46. M. Askegaard, J. E. and A. E. J. Sustainable management of potassium. In *Managing Soil Quality: Challenges in Modern Agriculture*; P. Schjønning, S. E. and B. T. C., Ed.; CABI Publishing: Wallingford Oxon OX10 8DE, 2004; pp. 85–102.

47. Huang SW, Jin JY, T. D. Crop Response to Long-Term Potassium application as affected by Potassium Supplying Power of the Selected Soils in Northern China. *Commun. Soil Sci. Plant Anal.* **2009**, 2833–2854.

48. Surapaneni, A.; Tillman, R. W.; Kirkman, J. H.; Gregg, P. E. H.; Roberts, A. H. C. Potassium-supplying power of selected Pallic soils of New Zealand. *New Zeal. J. Agric. Res.* **2002**, *45*, 113–122, doi:10.1080/00288233.2002.9513500.

49. Sadanandan, A. K.; Peter, K. V; Hamza, S. Role of Potassium Nutrition in Improving Yield and Quality of Spice Crops in India. In *Potassium for sustainable crop production*; Haryana and International Potash Institute, Switzerland, 2002; pp. 445–466.