



Farmers' fertilizer use gaps relative to government recommendations in the saline coastal zone of the Ganges Delta

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Abstract

Overuse or underuse of nutrients relative to recommendations is a likely cause of crop yield gaps and an impediment to the achievement of food security. Government-endorsed recommendations are developed to deliver the best evidence-based advice on balanced fertilizer; however, deviations of farmers' nutrient use from the recommendations are rarely examined. This study chose the salt-affected coastal zone of the Ganges Delta, where low crop productivity and cropping intensity by smallholders limit their income, to determine current nutrient use gaps for the first time of three cropping patterns in two representative districts of Bangladesh. A total of 246 farms were surveyed from three farm sizes. Farmers' nutrient use gaps were compared with Fertilizer Recommendation Guides published in 2012 (FRG-2012) and 2018 (FRG-2018). Relative to FRG-2012 recommendations, farmers used 12%, 70%, and 11% overdoses of N, P, and K, respectively, under two fully rice-based cropping patterns, but the level of overdoses increased with farm size. Rates of K (14%), S (28%), and Zn use were below the FRG-2012 recommendations, especially for the smallest category of farms. However, the FRG-2018, increased recommended N (5%), K (62%), S (12%), and Zn rates but reduced P (25%) rates for fully rice-based cropping patterns. In contrast with rice, regardless of farm size, farmers applied overdose nutrients to watermelon but compensated with underdoses in the subsequent monsoon rice implying that farmers prioritized fertilizer expenditure on the most profitable crop. For the cropping pattern with watermelon, farmers could reduce the use of N (69%) and P (46%) and increase the use of K (48%), S (5%), and B. Reducing NPK use gaps can save treasury for both the farmers and the governments by 39.1 and 73.8 USD ha⁻¹, respectively, under fully rice-based cropping patterns. Finally, our findings suggest there is scope to promote crop yields and sustainable intensification through balanced fertilizer use in a vulnerable saline region.

Keywords Bangladesh · Cropping pattern · Nutrient use gap · Nitrogen · Phosphorus · Potassium · Sulfur · Zinc

1 Introduction

Unbalanced (overuse or underuse) nutrient use relative to the government recommendations is a global concern that contributes to crop yield gaps, with many examples in developing and least-developed countries that demonstrate lost

opportunities for increased farm income and a threat to sustainable agriculture due to harmful off-site losses of nutrients (Dobermann et al. 2021). Overuse of one or more nutrients leads to wastage of nutrients and increased risk of environmental losses (Miao et al. 2011; Recous et al. 2019). On the other hand, 30–40% crop yield increase could be achieved

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through balanced (recommended) nutrient use practice in India (Murthy et al. 2015). In the salt-affected Ganges Delta, the application of balanced fertilizer can increase yield by 22% for monsoon rice (Hossain and Siddique 2020). Despite such evidence of the yield losses from an unbalanced fertilizer supply, farmers often use nutrients inefficiently to grow crops (Jahiruddin et al. 2010; Miah et al. 2019; Nasrin et al. 2019).

Mega-deltas which constitute ‘rice bowls’ of Asia are suffering from multiple climate change and basin water management impacts like sea-level rise, reduced river water flows, high soil salinity, storm and cyclone surges, and flooding (Mainuddin et al. 2019; Mandal et al. 2020). Due to high soil salinity and poor agronomic management practices especially in the Ganges Delta (Fig. 1), both cropping intensity (lands mostly remain fallow in dry season) and crop yields are very low relative to other regions (Bell et al. 2019). Moreover, the COVID-19 pandemic has also disrupted smallholder food production systems in delta regions like many other regions in the world (Goswami et al. 2021). Among various adverse impacts, low crop yield and low farm income of most of the smallholder farms are impediments to food security and rural livelihoods (Mainuddin et al. 2019). Indeed, it is reported that 19% of residents have one meal per day and 6% of them get substandard meals in the West Bengal coastal region of India (WCRI) (Sánchez-Triana et al. 2014). Another study which mainly focused on rural poor women of the south-west coastal region of Bangladesh (SCRB) found that food availability has decreased for 73% of families in the last 10–20 years due to the reduction of crop yield, reduction of employment, a decrease of income, and increase of food price (Parvin and Ahsan 2013). Most alarming, low crop yield and higher investment cost as a consequence of environmental constraints and inefficient fertilizer management are leading farmers towards negative preferences for rice cultivation that could be a

significant impediment to food security in the saline-affected coastal zone of the Ganges Delta (Aravindakshan et al. 2021).

Government-endorsed fertilizer recommendations are intended to provide farmers with the best current guidelines on profitable fertilizer use (FRG 2018). Moreover, the application of unbalanced nutrient rates in countries like Bangladesh that subsidize fertilizers represents a significant inefficiency in the use of budget support for sustainable development, especially in the agriculture sector (Huang et al. 2017). The cost of fertilizers, especially when subsidies are applied, influences fertilizer choices and rates. For example, in Bangladesh, the relative use of N, P, and K has changed in response to changes in subsidies offered for fertilizer types. Before 2009, farmers used low rates of P- and K-containing fertilizers compared with N-containing urea fertilizer due to subsidies only for the latter (Jahiruddin et al. 2010). After subsidies increased on P and K fertilizer, their use increased almost 157% and 119%, respectively, from 2010 to 2019, while N use increased only 14% (FAO 2021). However, farmers’ fertilizer use decisions also depend on cropping pattern, cropping season, fertilizer availability, financial status, previous fertilizer usage, crop performance, soil quality, land topography, and various influential factors like advice from fertilizer traders, extension agents, etc. (Miah et al. 2019). In addition, the influence of peer farmers, a focus on profit for individual crops, the inclusion of staple food crops in the cropping pattern, lack of soil testing access, and adherence to conventional fertilizer practices are commonly reported barriers to recommended fertilizer use practices (Baral et al. 2020; Miah et al. 2019; Ren et al. 2021). However, the correspondence between farmers’ fertilizer rates and government-recommended fertilizer rates is rarely reported. Most of the previous studies considered single crops rather cropping patterns during fertilizer use gap assessment, and single nutrients rather than the full range of fertilizers or nutrients

Fig. 1 Field condition (left) in the dry season in the south coastal region of Bangladesh. Most of the cultivable land remains fallow after harvest of the monsoon rice due to high soil salinity, but stored water creates opportunities for dry season irrigated crops. Farmers are using fertilizer (right) in the rice crop but a lack of knowledge about Government-endorsed recommended fertilizer doses results in rice yield gaps and low farming profitability. Photograph by Md. Shofiqul Islam



recommended by the government organizations (Basak et al. 2015; Jahiruddin et al. 2010; Miah et al. 2019). Moreover, the fertilizer use gap studies generally did not consider the losses to farmers and the government treasury due to unbalanced fertilizer rates. In the current study, for the first time, we examine the nutrient use gaps in diverse rice-based cropping patterns in the saline coastal zone of the Ganges Delta.

Due to land and groundwater salinity and insufficient fresh water for dry season irrigation, agricultural production is greatly hampered in the coastal zone of the Ganges Delta (Mainuddin et al., 2019; Bell et al., 2019). For a zone with significant soil and environmental constraints, it is essential to understand farmers' decision-making around fertilizers and in particular whether farmers are using balanced fertilizers or likely to gain the benefit of sustainable intensification through the use of recommended fertilizer rates. We primarily hypothesise that assessment of farmers' current nutrient use gaps relative government-endorsed recommendations taking appropriate measures to reduce the gaps can increase crop yields and farming profitability and promote sustainable intensification in the salt-affected Ganges Delta. To test the hypothesis, a survey was conducted in two representative saline-affected districts of southern Bangladesh to estimate farmers' current nutrient use gaps for pre-monsoon rice, monsoon rice, and watermelon grown in three rice-based cropping patterns by comparing two government-endorsed Fertilizer Recommendation Guides (FRG): FRG-2012 which was current at the time of the survey and FRG-2018 which was disseminated in the study areas after the survey was completed. This paper also discusses farmers' conceptions, derived from focus group discussions (FGD) and key informant interviews (KII), regarding their fertilizer use and its relationship to current nutrient use gaps in the saline coastal zone of the Ganges Delta.

2 Materials and methods

2.1 Study areas and cropping patterns

This study was conducted in the Ganges Tidal Floodplain Agro-ecological Zone (AEZ-13) which contains saline soils and covers about 49% of the SCRB (SRDI 2010). We selected two districts from AEZ-13, namely Barguna and Khulna districts, which are highly affected by salinity due to their close proximity to the Bay of Bengal (Hasan et al. 2019). Dacope and Amtali *Upazilas* (sub-district) were selected from Khulna and Barguna districts, respectively. Then three agriculture blocks (ABs) from each *Upazila* were selected with the probability proportional to size (PPS) sampling procedure (Table 1). For providing extension services among farmers, the Department of Agricultural Extension (DAE), Bangladesh, sub-divided each Sub-*Upazila* into segments,

called AB, each covering an area of about 2,000 ha. One Sub Assistant Agriculture Officer (SAAO) is in-charge of one AB. In the study, each AB represents one cropping pattern.

Most of the cultivable land of SCRB remains fallow in the dry season due to soil salinity, scarcity of good quality irrigation water, prolonged waterlogging due to untimely rainfall in the late monsoon season, and delayed rice harvest (Mainuddin et al. 2019). The dominant crop grown is transplanted monsoon rice with low yields (Bell et al. 2019). About 86% of Dacope, Khulna, land was under single monsoon rice, though some farmers also cultivated watermelon in the dry season (*Rabi*) using canal and pond water (DAE, 2019). Watermelon is gaining popularity in this region as it is more profitable than other *Rabi* crops due to its high market price and demand, tolerance of soil salinity, and compatibility with the monsoon rice in a cropping pattern. Considering this site-specific information, two cropping patterns were selected from Dacope *Upazila* namely *fallow-fallow-monsoon rice* (also called *T. Aman* rice) and *watermelon-fallow-monsoon rice*.

Some farmers also cultivated pre-monsoon rice (also called *T. Aus* rice) at Amtali, Barguna, using early monsoon rainfall and pond water and then planted a following monsoon rice crop (DAE 2019). For that reason, *fallow-pre-monsoon rice-monsoon rice* cropping pattern was considered from Amtali. Other crops such as irrigated rice, groundnut, sunflower, and grass pea were cultivated by small numbers of farmers but were not considered in this study. Based on the highest area coverage, one AB named *Chila* was selected for *fallow-pre-monsoon rice-monsoon rice* cropping pattern from Amtali, Barguna district (DAE 2019).

2.2 Sample design and survey administration

Before the field survey, a draft interview schedule was prepared for field testing. Key modules included in the interview schedule were information on socio-demographic characteristics, existing cropping patterns, crop-wise input rates (fertilizer and other nutrient inputs) under specific cropping patterns, existing soil fertility management techniques, etc. After pre-testing, the interview schedule was improved and finalized. Then the primary data were collected through face-to-face interviews by the trained enumerators with close supervision by the research team from January 2019 to April 2019. Only experienced farm households who cultivated crops at least for the last 5 years were interviewed. While all farms are considered to be smallholders, data were collected from three designated farm sizes, referred to as (a) small-scale farmer (<1.01 ha), (b) medium-scale farmer (1.01-3.03 ha), and (c) large-scale farmer (>3.03 ha) (BBS 2013) as research suggested that the rates of fertilizer use differ with farm size (Jahiruddin et al. 2010; Nasrin et al. 2019). The study followed a stratified random sampling technique to collect samples from different

Table 1 Sample design and survey administration of the study. Abbreviations: *FGD* Focus group discussion, *KII* Key informant interview, *LF* Large-scale farmers, *MF* Medium-scale farmers, *SF* Small-scale farmers

Cropping pattern	Tools used in the study	Selected district	Selected upazila (sub-district)	Selected agricultural block	Sample distribution
Fallow-fallow-monsoon rice	Field survey	Khulna	Dacope	Baruikhali	Field survey (82×3)=246
Watermelon-fallow-monsoon rice	FGD KII	Khulna	Dacope	Bajua	82 samples under each cropping pattern (SF=54, MF=24, LF= 4)
Fallow-pre-monsoon rice-monsoon rice		Barguna	Amtali	Chila	FGD (10×3)=30 10 participants in each FGD KII (2×3)=6 Two participants under each cropping pattern

farm sizes. Before data collection, a complete list of farmers according to farm size was prepared with the help of the Upazila Agriculture Officer (UAO) in each respective *Upazila*. Finally, a total of 246 samples were selected randomly from the three farm sizes, taking 82 samples under each cropping pattern for the field survey. Focus group discussions (FGD) and key informant interviews (KII) were also conducted to triangulate the findings (Table 1). Ten people participated in each FGD. For KII, two key informants were selected under each cropping pattern.

2.3 Nutrients for gap identification

This study considered only those nutrients which are recommended by the FRG. The FRG is a government-endorsed guide that recommends macronutrients and micronutrients based on crop needs relative to a yield goal. It provides AEZ-based nutrient recommendations considering cropping patterns, land topography, soil type, soil test result, and residual effect of nutrients. Three limiting essential macronutrients, N, P, and K; one secondary nutrient S; and one micronutrient, Zn, were recommended by the FRG for rice crops in diverse rice-based cropping patterns under AEZ-13. Additionally, B was recommended for watermelon in the *watermelon-fallow-monsoon rice* cropping pattern. For the remaining nutrients, it was assumed that uptake of those nutrients from the soil, including inputs from the air, water, and plant residues, was not limiting (Basak et al. 2015).

2.4 Analytical technique

For determining the nutrient use gap, we followed three steps. First, we determined farmers' current nutrient use from different quantifiable sources (chemical fertilizers and organic manures like cow-dung, poultry litter, crop residues, etc.) of nutrients. Organic manures including crop residues are sources of both macro and micronutrients (see Supplementary Table 2). Generally, farmers retain no or low amounts of crop

residues in the field because of sales of residues (rice straw) or use in the household as animal feed and fuel. The amount of retained residues was more or less the same for all categories of farmers (see Supplementary Table 1). Farmers do not measure the amounts of crop residues, but they can estimate it from their farming experience. The crop residue data were triangulated during the FGD and KII. The adulteration rate of major subsidized chemical fertilizers (urea, TSP, DAP, and MoP) is less than 5%, but 78% of micronutrients sold in the local markets {zinc sulfate (mono-hydrate and hepta-hydrate)} fail to meet the certified nutrient concentrations (SRDI 2019). Most of the chemical fertilizers and organic manures including crop residues contain more than one nutrient element (see Supplementary Table 2). Each available farmer's sources of nutrients (see Supplementary Table 1) were totaled after multiplying the mass applied by their nutrient concentration for calculating the farmers' current nutrient use. The following equation was developed based on existing literature and farmers' available sources of nutrients in the study areas to determine the current nutrient use of all categories of farmers:

$$\sum_{i=1}^n N_{rikl} = \sum_{i=1}^n \left\{ X_{f_n} * C_{rf_n} + \left(\frac{X_{m_n}}{2} \right) * C_{rm_n} + \left(\frac{X_{j_n}}{2} \right) * C_{rj_n} \right\} \quad (1)$$

Where,

N_{rikl} = Current use of r nutrient (kg ha⁻¹) in the kth plot by the ith farmer for lth crop

X_{f_n} = Use of nth chemical fertilizer (kg ha⁻¹) containing r nutrient

X_{m_n} = Use of nth organic manures (cow-dung, poultry litter, etc.) (kg ha⁻¹)

X_{j_n} = Amount of crop residue (kg ha⁻¹) retain from the previous nth crop

C_{rf_n} = r nutrient composition (%) within nth chemical fertilizer

C_{rm_n} = r nutrient composition (%) within nth organic manures

C_{rj_n} = r nutrient composition (%) within nth crop residue

Approximately 50% of the nutrients added by cow dung (decomposed) or poultry litter are assumed to be available for uptake by crops (FRG 2018). The studies also reported that at least 50% of the nutrients left in crop residues are available for the subsequent crop cultivated (FRG 2018; Torma et al. 2018). Hence, we added all the used chemical fertilizers (kg ha⁻¹) and half of the nutrient input of applied cow dung, poultry litter, and remaining crop residues (kg ha⁻¹) of the previous crop to calculate the total of specific nutrient inputs (kg ha⁻¹) from chemical fertilizers and organic manures, respectively. There are other sources of crop nutrients like rainfall, irrigation water, air deposition, residual supply from previous fertilizer applications within cropping patterns etc., but the study did not quantify their contribution due to unavailability of data.

Secondly, the FRG was followed for nutrient recommendations for each rice-based cropping pattern. During the data collection period, the FRG-2012 was available to farmers. A new FRG (i.e., FRG-2018) which was officially disseminated in the study areas after our survey was completed. So, the study compared the nutrient use gaps for both the FRG-2012 and the newly published FRG-2018.

Finally, calculations were completed to determine the nutrient use gaps between farmers' current nutrient use and FRG recommended nutrient dose. Using Eq. 2, we subtracted for each farm the current nutrient use from the recommended nutrient dose.

$$D_{ir} = N_{ir} - R_{ir} \quad (2)$$

where D_{ir} = current nutrient use gap of r nutrient (kg ha⁻¹) by the i^{th} farmer; N_{ir} = current use of r nutrient (kg ha⁻¹) by the i^{th} farmer; R_{ir} = recommended dose of r nutrient (kg ha⁻¹) for either FRG-2012 or FRG-2018. If, $D_{ij}=0$, that indicates no nutrient use gap; "+" sign indicates overdose of r nutrient and "-" sign indicates underdose of r nutrient.

We also calculated the financial loss of both the farmers and the Government of Bangladesh because of using overdose of nutrients by the farmers under each cropping pattern. The loss was calculated only for NPK nutrients because these nutrient-containing chemical fertilizers are subsidized in Bangladesh. At first, the NPK nutrients were converted to equivalent rates of chemical fertilizers. Then both the farmer's and government's losses were calculated by using Equations (3) and (4), respectively.

$$F_{int} = O_{inf} \times F_{nfp} \quad (3)$$

$$G_{int} = O_{inf} \times G_{nfs} \quad (4)$$

where F_{int} = financial loss of the i^{th} farmer for using overdose of the n^{th} chemical fertilizer in the cropping season; G_{int} = financial loss of the government for using overdose of the n^{th} chemical fertilizer by the i^{th} farmer; O_{inf} = cumulative rates of

overdose use (kg ha⁻¹) of the n^{th} chemical fertilizer under the cropping pattern relative to FRG recommendation by the i^{th} farmer; F_{nfp} = maximum retail price (USD) per kg of n^{th} chemical fertilizer in the local market for the farmers (fixed by the Government of Bangladesh); and G_{nfs} = amount of government subsidy (USD) per kg for the n^{th} chemical fertilizer.

To calculate G_{nfs} , Equation (5) was used as follows,

$$G_{nfs} = G_{pnf} - D_{pnf} \quad (5)$$

where G_{pnf} = the total government procurement cost (for imported fertilizers) per kg of the n^{th} fertilizer (USD) and D_{pnf} = fertilizer dealers purchase price (USD) per kg of the n^{th} fertilizer (fixed by the Government of Bangladesh).

Since the government sells chemical fertilizers only to appointed fertilizer dealers, G_{nfs} was calculated by subtracting the total government procurement cost (for imported fertilizer) per kg of the n^{th} fertilizer from the fertilizer dealers' purchase price per kg of n^{th} fertilizer, after deducting the subsidy.

3 Results

3.1 Descriptive statistics of socio-demographic characteristics

The average farm size ranged from 0.5 to 0.6 ha for small-scale farms, 1.5 to 1.6 ha for medium-scale farmers, and 3.4 to 3.7 ha for large-scale farmers (Table 2). Only 10% of farmers in the study areas received training regarding soil nutrient management. Very few farmers (6% only) tested their soil due to a lack of accessible soil testing facilities and motivation. Approximately 77% of small-scale farmers used fertilizer based on advice from fertilizer dealers, peer farmers, and their own experience rather than Government extension agents (Table 2). About 83% of farmers reported no knowledge about the FRG or its recommended fertilizer doses. The large- and medium-scale farmers received 24% and 16% more credit access than the small-scale farmers under *fallow-pre monsoon rice-monsoon rice* cropping pattern, respectively, but credit was accessible 22% more for small-scale farmers under cropping pattern with high-value watermelon crop relative to fully rice-based *fallow-pre monsoon rice-monsoon rice* cropping pattern (Table 2).

3.2 Nutrient use gaps under *fallow-pre monsoon rice-monsoon rice* cropping pattern

Relative to FRG-2012, all categories of farmers applied overdoses of N and P in the pre-monsoon rice (Fig. 2), but the magnitude of the overdose was higher for large- and medium-scale farmers compared to small-scale farmers (Fig. 2ab).

Table 2 Socio-demographic characteristics of the farmers in diverse rice-based cropping patterns in the study areas. Abbreviations: *LF* Large-scale farmers, *MF* Medium-scale farmers, *SF* Small-scale farmers, *FRG* Fertilizer Recommendation Guide, *SAAO* Sub Assistant Agriculture Officer. Source: Field survey, 2019

Particulars	Fallow-pre-monsoon rice-monsoon rice			Fallow-fallow-monsoon rice			Watermelon-fallow-monsoon rice			All farmers (n=246)
	LF (n=4)	MF (n=24)	SF (n=54)	LF (n=4)	MF (n=24)	SF (n=54)	LF (n=4)	MF (n=24)	SF (n=54)	
Age (years)	47.8	46.1	44.6	46.0	43.2	39.1	44.0	43.0	40.1	42.3
Education (years)	7.5	7.0	3.9	9.3	6.7	5.2	10.0	7.8	5.8	5.8
Farming experience (years)	26.8	23.6	22.3	25.5	21.4	18.6	23.8	22.2	20.4	21.2
Farm size (ha)	3.4	1.6	0.6	3.6	1.5	0.5	3.7	1.6	0.6	1.01
Land typology (%)										
Highland	25.0	8.3	1.9		12.5	5.6	25.0	20.8	1.8	6.9
Medium highland	50.0	54.2	51.9	100	50.0	44.4	75.0	66.7	59.3	54.9
Lowland	25.0	29.2	31.5		25.0	31.5		12.5	27.8	26.4
Very lowland		8.3	14.8		12.5	18.5			11.1	11.8
Gender (%)										
Male	100	100	100	100	100	100	100	100	100	100
Crop farming related training (%)	50.0	33.3	18.5	75.0	37.5	20.4	50.0	29.2	11.1	23.6
Soil nutrient management related training (%)	25.0	16.7	5.6	25.0	20.8	9.3		8.3	3.7	9.3
Farmers tested their Soil (%)		12.5	3.7	25.0	12.5	5.6		8.3	1.9	6.1
Knowledge about optimum dose and FRG (%)	25.0	25.0	11.1	25.0	29.2	18.5	25.0	16.7	9.3	16.7
Decision regarding fertilizer application (%)										
Advice from SAAO	50.0	33.3	16.7	75.0	33.3	20.4	25.0	33.3	13.0	23.2
Advice from fertilizer dealers and peer farmers	25.0	37.5	37.0	-	29.2	35.2	50.0	54.2	75.9	45.5
Own experience	25.0	29.2	46.3	25.0	37.5	44.4	25.0	12.5	11.1	31.3
Distance of input market (km)	4.6	4.9	3.6	4.0	3.9	3.7	4.9	3.8	4.4	4.02
Member of any organization (%)	75.0	37.5	22.2	75.0	45.8	31.5	50.0	33.3	24.1	30.5
Received credit (%)	50.0	41.7	25.9	50.0	58.3	37.0	75.0	66.7	48.2	43.5
Livestock/household (no.)										
Cattle	4	3	3	4	4	3	3	4	4	3
Goat and sheep	3	2	2	3	2	3	4	3	3	2
Poultry	17.5	20.1	18.6	12.5	17	15	11	10	12	15

Relative to the K recommendations in the FRG-2012, along with the removal of rice residue, which is one of the key sources of K (see Supplementary Table 2), K supply to pre-monsoon rice was underdosed by the small-scale farmers only (Fig. 2c). Similarly, all categories of farmers used underdoses of S and Zn. However, relative to the FRG-2018, which increased the N and K recommendations (7.0 and 28 kg ha⁻¹, respectively) for pre-monsoon rice, all farmers need to substantially increase rates of K (23.4–29.8 kg ha⁻¹), while large- and medium-scale farmers could decrease P (4.3 and 5.9 kg ha⁻¹, respectively) use in pre-monsoon rice. Only modest adjustments in N fertilizer (± 5 kg N ha⁻¹) would be required according to FRG-2018.

Similar to pre-monsoon rice, relative to the FRG-2012, all categories of farmers used overdoses of N and P in

monsoon rice (Fig. 3) but used underdoses of K, S, and Zn, especially by the small-scale farmers (Fig. 3c). The FRG-2018 which substantially increased N and K recommendations (15 and 32 kg ha⁻¹, respectively) and decreased the P recommendation (2 kg ha⁻¹) for monsoon rice recommends that all farmers need to marginally increase rates of N and substantially increase K use (13.2 and 35.9 kg ha⁻¹, respectively) while all farmers could decrease rates of P use (6.4–10.4 kg ha⁻¹, respectively) (Fig. 3).

3.3 Nutrient use gaps under fallow-fallow-monsoon rice cropping pattern

Relative to the FRG-2012, all categories of farmers used overdoses of N and P in monsoon rice under the *fallow-*

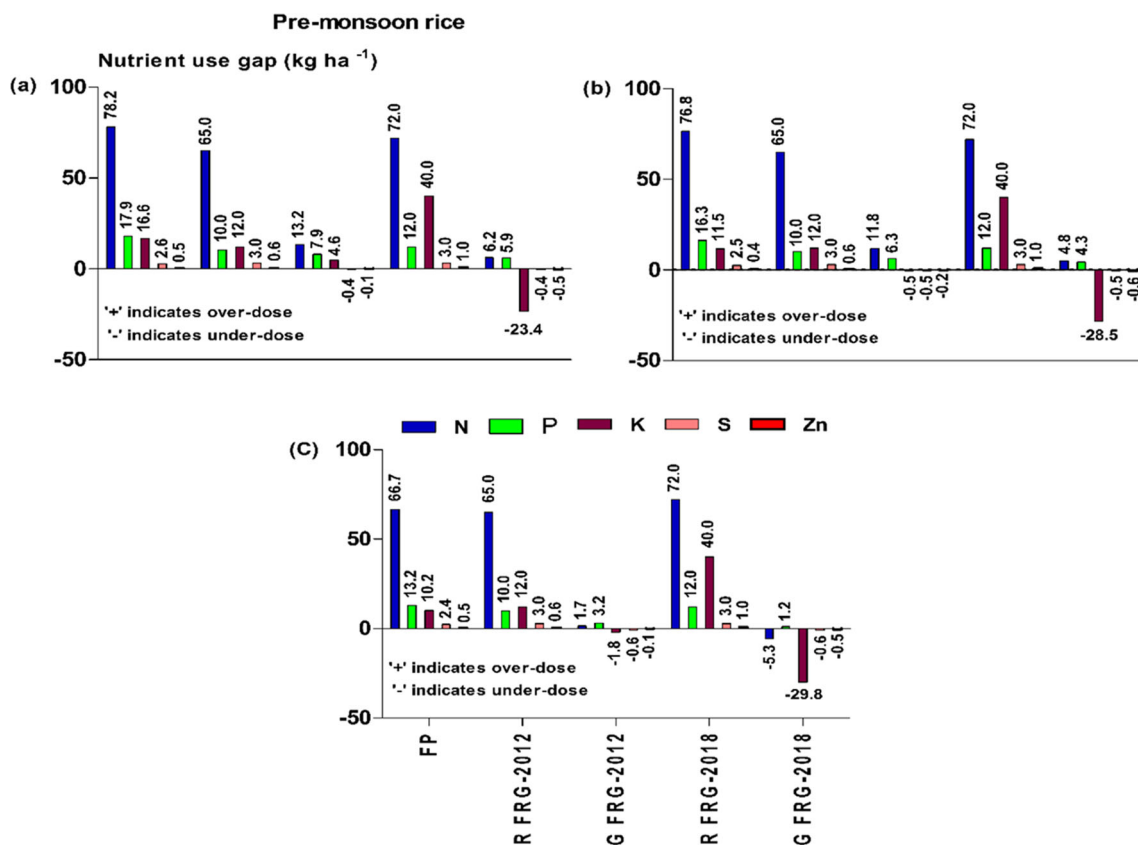


Fig. 2 Farmers' current nutrient use gaps relative to the Fertilizer Recommendation Guide (FRG) in pre-monsoon rice: **a** large-scale farms, **b** medium-scale farms, and **c** small-scale farms under *fallow-pre-monsoon rice-monsoon rice* cropping pattern. Yield goal for providing recommendations: $4.0 \pm 0.4 \text{ t ha}^{-1}$. Abbreviations: *FP* farmers practice, *R*

FRG-2012 Nutrient recommendations as per FRG-2012, *G FRG-2012* Nutrient use gaps as per FRG-2012, *R FRG-2018* Nutrient recommendations as per FRG-2018 and *G FRG-2018* Nutrient use gaps as per FRG-2018

fallow-monsoon rice cropping pattern (Fig. 4). The over-dose level of N and P was high relative to that of monsoon rice grown in the other selected cropping patterns. Similar to the *fallow-pre-monsoon rice-monsoon rice* cropping pattern, the rates of S and Zn use were at underdose levels for small-scale farmers (Fig. 4c). The FRG-2018 which increased recommendations of NPK (15, 5.0, and 32 kg ha⁻¹, respectively) for monsoon rice relative to FRG-2012, small-scale farmers need to increase rates of N and K (11.8 and 33.2 kg ha⁻¹, respectively) while large- and medium-scale farmers need to increase K rates (21.4 and 26.1 kg ha⁻¹, respectively) and reduce rates of P (5.3 and 4.1 kg ha⁻¹, respectively) use in monsoon rice (Fig. 4ab).

We also calculated the cumulative nutrient use gaps for NPKS only in the whole cropping season relative to cumulative recommended doses for the two fully rice-based cropping patterns (see Supplementary Table 3). We found that relative to the FRG-2012, all three categories of farmers used, on average, 12%, 70%, and 11% overdoses of NPK, respectively in the cropping season under *fallow-fallow-monsoon rice* and *fallow-pre-*

monsoon rice-monsoon rice cropping patterns, but used underdoses of NKS (5%, 62%, and 12%, respectively) relative to FRG-2018.

3.4 Nutrient use gaps under *watermelon-fallow-monsoon rice* cropping pattern

All categories of farmers used high overdoses of NPK in watermelon relative to FRG-2012 under the *watermelon-fallow-monsoon rice* cropping pattern, but underdoses of S, Zn, and B (Fig. 5). The overdose level of NPK was higher for medium- and large-scale farmers relative to small-scale farmers. Even though the FRG-2018 significantly increased N and K recommendations (20 and 27 kg ha⁻¹, respectively) and decreased the S (5 kg ha⁻¹) recommendation for watermelon relative to FRG-2012, the farmers, especially large-scale farmers, can decrease rates of N and P (185.8 and 28.1 kg ha⁻¹, respectively) while all farmers need to apply more K and small-scale farmers need to increase the rates of Zn and B use (0.4 and 0.8 kg ha⁻¹, respectively) in watermelon (Fig. 5).

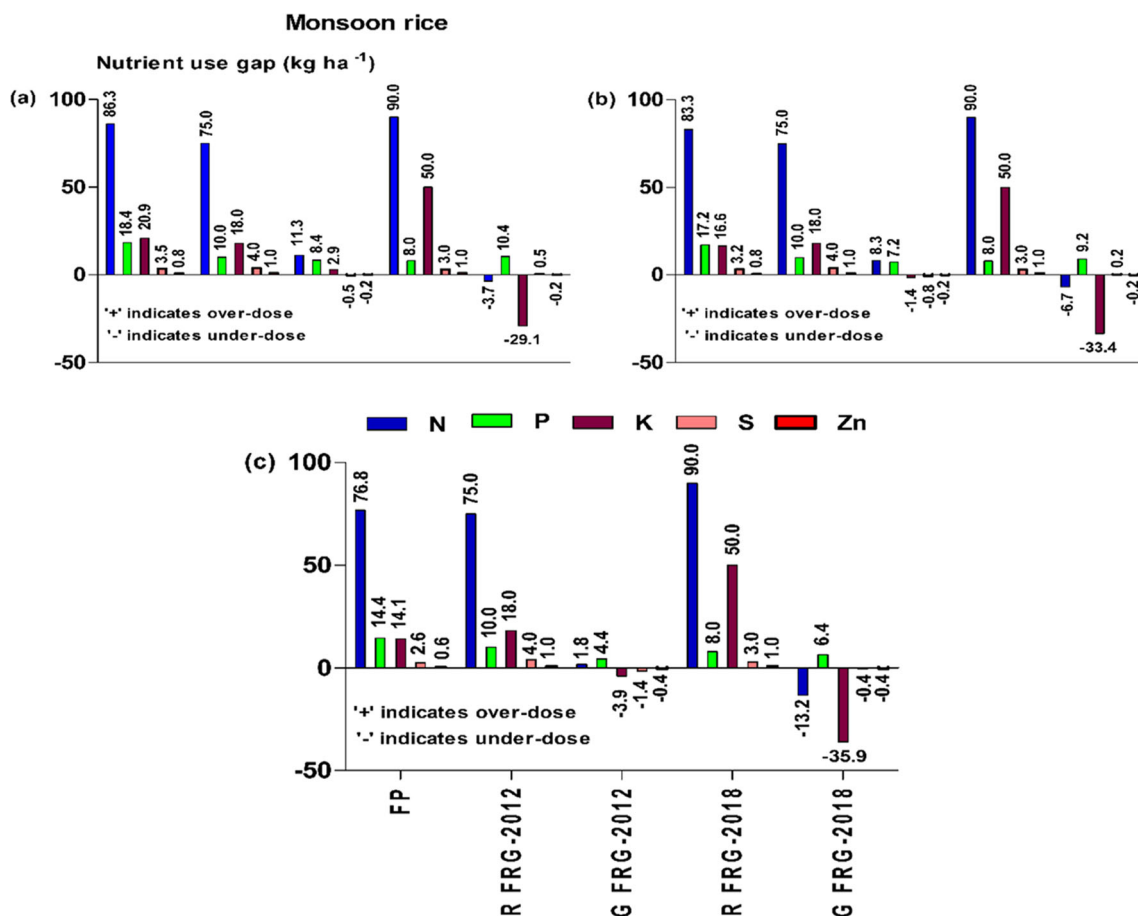


Fig. 3 Farmers' current nutrient use gaps relative to the Fertilizer Recommendation Guide (FRG) in monsoon rice: **(a)** large-scale farms, **(b)** medium-scale farms, and **(c)** small-scale farms under *fallow-pre-monsoon rice-monsoon rice* cropping pattern. Yield goal for providing recommendations: $5.0 \pm 0.5 \text{ t ha}^{-1}$. Abbreviations: *FP* farmers practice, *R*

FRG-2012 Nutrient recommendations as per FRG-2012, *G FRG-2012* Nutrient use gaps as per FRG-2012, *R FRG-2018* Nutrient recommendations as per FRG-2018 and *G FRG-2018* Nutrient use gaps as per FRG-2018

In the monsoon rice crop which follows watermelon, all categories of farmers used high underdoses of nutrients (Fig. 6). The underdose gap was very wide for small-scale farmers (Fig. 6c). The FRG-2018, which highly increased recommendations of N and K (15 and 32 kg ha⁻¹, respectively) for monsoon rice relative to FRG-2012 indicates that farmers especially small-scale farmers should increase rates of NPK (36.1, 4.1 and 40.5 kg ha⁻¹, respectively) in monsoon rice following watermelon.

We also estimated that, on average, farmers used 106%, 49%, and 20% overdoses of N, P, and K in the cropping season, respectively, relative to the FRG-2012 recommendations under the cropping pattern with high-value watermelon (see Supplementary Table 3). Similar to fully rice-based cropping patterns, relative to FRG-2018, all categories of farmers used, on an average, 48% and 5% underdose of K and S, respectively, for the *watermelon-fallow-monsoon rice* cropping pattern.

3.5 Crop yield difference among farmers with varying levels of nutrient use gaps

We examined farmers' crop yield difference under diverse levels of nutrient use gaps (Fig. 7). Since all categories of farmers used overdoses or underdoses of nutrients, we determined a threshold range ($\pm 10\%$ deviation of cumulative nutrient use rates in the cropping season from total recommendations) which was treated as following the recommended dose. If farmers used more than 10% above the recommended rate of nutrients, this value was treated as an overuser, and vice-versa. For the fully rice-based cropping patterns (Fig. 7bc), we found three categories (under-user, recommended-dose user, and over-user) as per the FRG-2012 recommendations. As cumulative nutrient use rates were very high under the *watermelon-fallow-monsoon rice* cropping pattern, there were only two categories (the recommended-dose user and over-user) for both FRG-2012 and FRG-2018 recommendations (Fig. 7a).

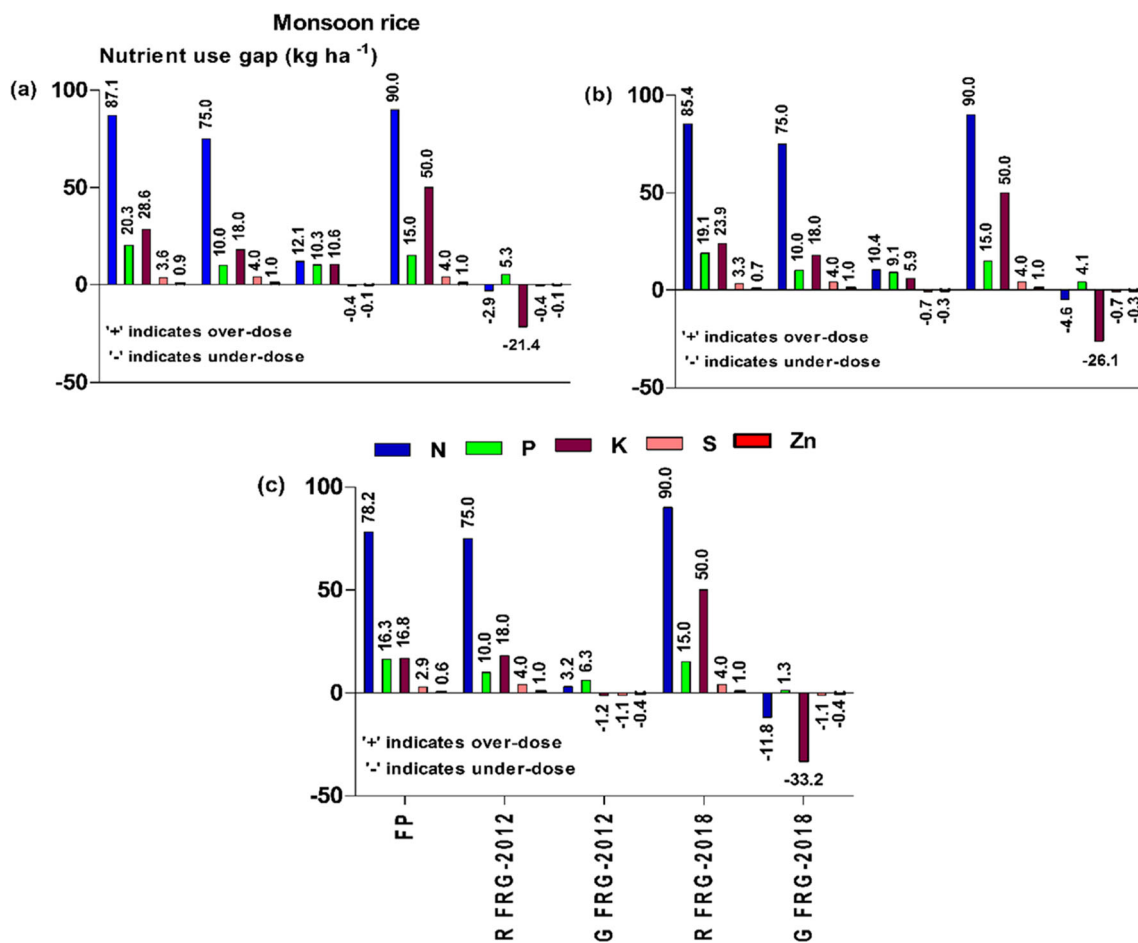


Fig. 4 Farmers' current nutrient use gaps relative to the Fertilizer Recommendation Guide (FRG) in monsoon rice: **a** large-scale farms, **b** medium-scale farms, and **c** small-scale farms under *fallow-fallow-monsoon rice* cropping pattern. Yield goal for providing recommendations: 5.0 ± 0.5 t ha⁻¹. Abbreviations: *FP* farmers practice,

R FRG-2012 Nutrient recommendations as per FRG-2012, *G FRG-2012* Nutrient use gaps as per FRG-2012, *R FRG-2018* Nutrient recommendations as per FRG-2018 and *G FRG-2018* Nutrient use gaps as per FRG-2018

Only 18 to 34% of farmers used nutrients close to recommendations under the selected cropping patterns (Fig. 7). However, the over-user farmers got higher pre-monsoon and monsoon rice yields (3.8 and 4.3 t ha⁻¹, respectively) compared to the recommended-dose user (3.5 and 3.8 t ha⁻¹, respectively) under *fallow-pre-monsoon rice-monsoon rice* cropping pattern as per the FRG-2012 recommendation (Fig. 7c). Relative to FRG-2018 recommendations, however, the recommended-dose user got higher pre-monsoon and monsoon rice yield (3.9 and 4.4 t ha⁻¹, respectively) than the under-user category of farmers. In the *watermelon-fallow-monsoon rice* cropping pattern, the recommended-dose user got a higher monsoon rice yield (3.8 and 3.9 t ha⁻¹, respectively) as per both FRG-2012 and FRG-2018 recommendations compared to the over-user categories of farmers (3.5 and 3.4 t ha⁻¹, respectively) (Fig. 7a). Although the over-user farmers got a higher yield in watermelon relative to FRG-2018 recommendations, yields for recommended-dose user and over-user were statistically non-significant (Fig. 7a; see also

Supplementary Table 4). The result also indicates gaps between farmers' yield and attainable yield was very high for all categories of farmers (Fig. 7).

3.6 Financial loss for using overdose of nutrients

For calculating the financial loss, the NPK nutrients were converted to equivalent rates of urea, TSP, and MoP fertilizers, respectively. The result indicates that both the government and farmers incurred large losses of money (USD ha⁻¹) because of overdose of nutrients by the farmers since the government procurement price of per kg of fertilizers was high relative to farmers purchasing price in the local market (Table 3). The estimated financial loss for both farmers and the government was much higher for the cropping pattern with high-value watermelon (99.8 and 128.3 USD ha⁻¹, respectively) compared to the two fully rice-based cropping patterns (39.1 and 73.8 USD ha⁻¹, respectively) in the saline coastal zone of the Ganges Delta (Table 3).

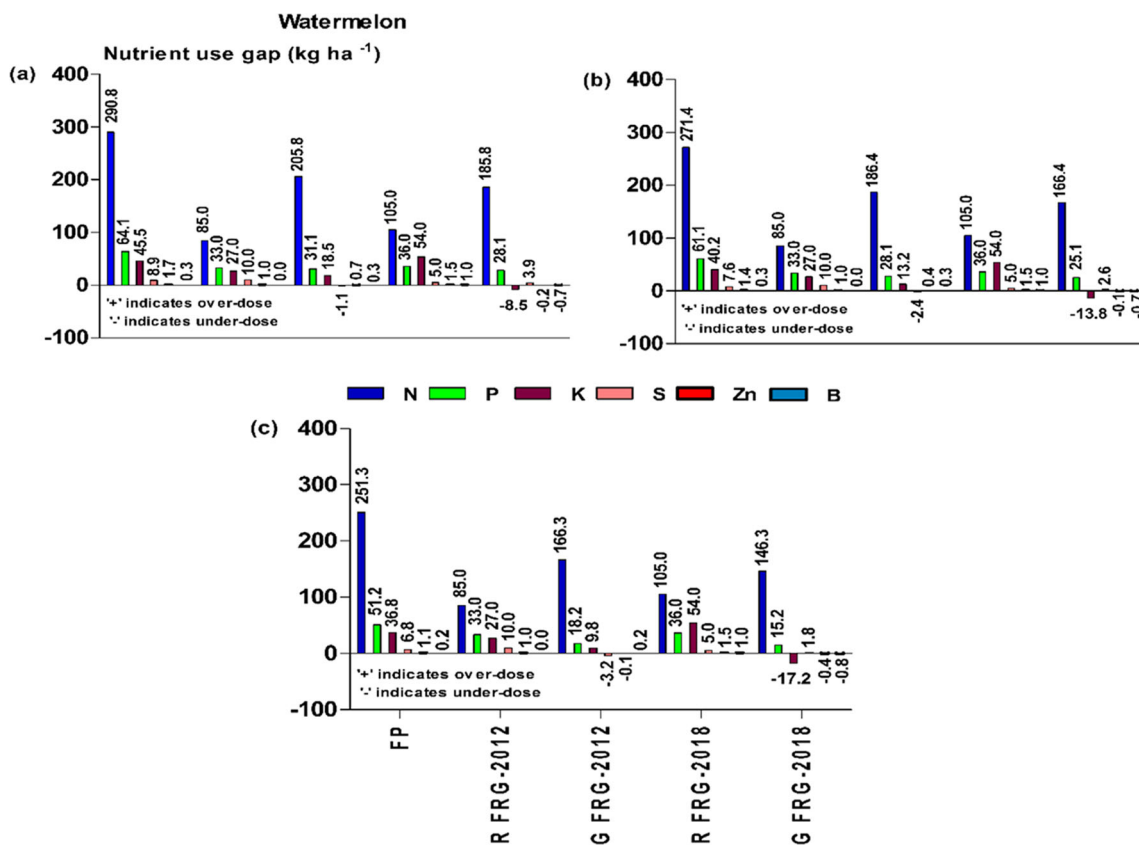


Fig. 5 Farmers’ current nutrient use gaps relative to the Fertilizer Recommendation Guide (FRG) in watermelon: **a** large-scale farms, **b** medium-scale farms, and **c** small-scale farms under *watermelon-fallow-monsoon rice* cropping pattern. Yield goal for providing recommendations: 60.0 ± 6.0 t ha⁻¹. Abbreviations: *FP* farmers practice,

R FRG-2012 Nutrient recommendations as per FRG-2012, *G FRG-2012* Nutrient use gaps as per FRG-2012, *R FRG-2018* Nutrient recommendations as per FRG-2018 and *G FRG-2018* Nutrient use gaps as per FRG-2018

4 Discussion

Government agencies generally prepare fertilizer recommendation guides for farmers which are presumed to represent best practices based on empirical research and expert opinion. However, farmers’ use and adherence to these guidelines are rarely examined. Failure of farmers to follow government-endorsed recommendations may be a significant cause of gaps between farmers’ yields and what is attainable in those growing conditions. Conversely, overcoming the yield gap through balanced fertilizer additions by farmers is an opportunity for improving food security provided there is a clear diagnosis of the changes required in farmers’ fertilizer use. The coastal zone of the Ganges Delta is an area of low cropping intensity and lower farm incomes relative to the rest of Bangladesh, and hence a useful case study region in which to examine these propositions.

4.1 Farm size and fertilizer use rates

Rates of fertilizer use and the prevalence of underdosing or overdosing were strongly related to farm size.

Generally, small-scale farmers of the SCRB have lower household liquidity which is exacerbated by vulnerability to various natural calamities (Verschuur et al. 2020). During the FGD, farmers of the study areas reported that their access to credit from commercial banks is limited for fertilizers especially for low-yield and low profit-potential rice crops, forcing them to arrange credit from local non-government organizations or other money lenders with high interest rates. When farmers buy fertilizer on credit from fertilizer dealers, they pay higher prices per kilogram than those from the government-prescribed fertilizer price due to the transactional costs of re-packaging fertilizer into small quantities (Miah et al. 2019). On the other hand, small-scale households tend to use higher rates of organic manures produced on their own farm relative to medium- and large-scale farmers (Parvin and Ahsan 2013) (see Supplementary Table 1).

On the other hand, medium- and large-scale farmers are financially better off and preferred chemical fertilizer more than that of organic manure because the preparation and sourcing of organic manure for the fields are labor-intensive and time-consuming (Kishore et al. 2021). In

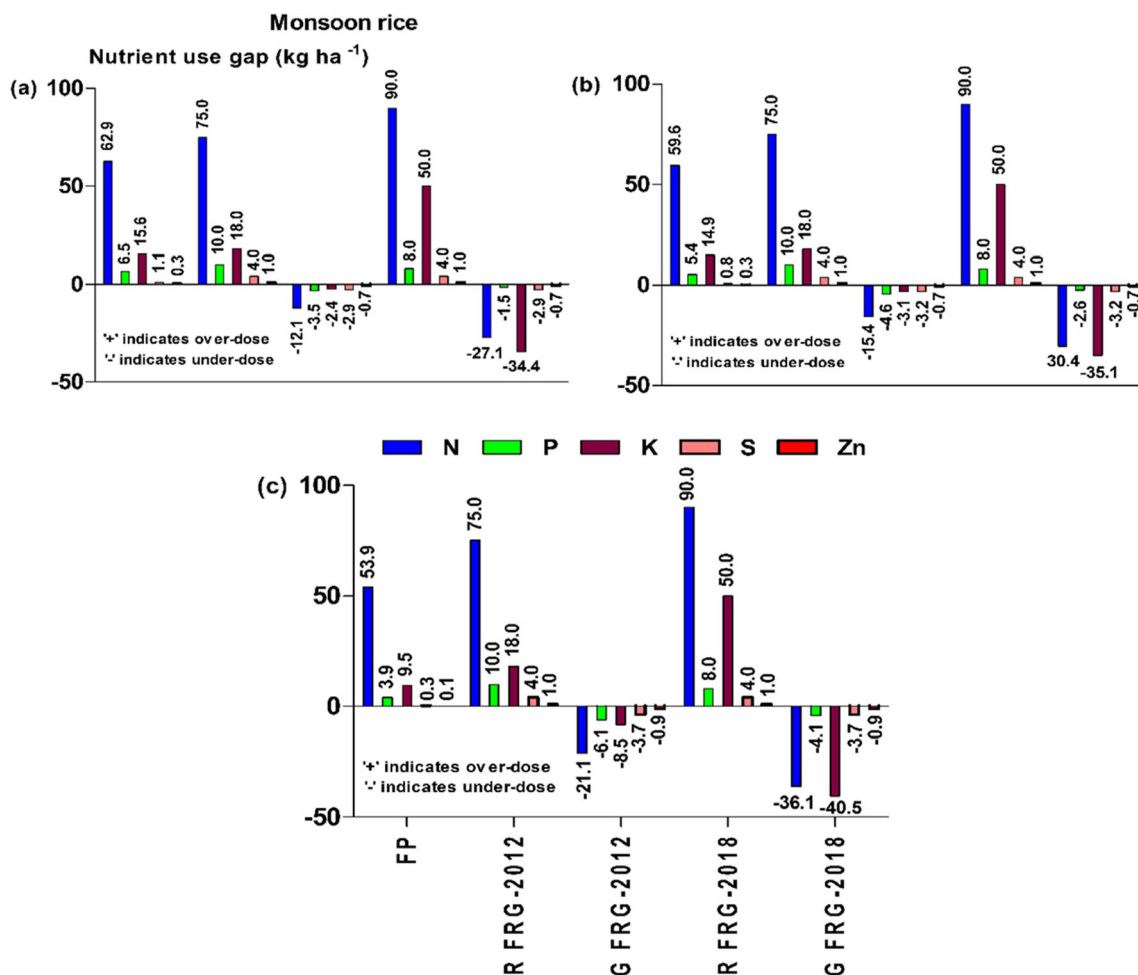


Fig. 6 Farmers' current nutrient use gaps relative to the Fertilizer Recommendation Guide (FRG) in monsoon rice: **a** large-scale farms, **b** medium-scale farms, and **c** small-scale farms under *watermelon-fallow-monsoon rice* cropping pattern. Yield goal for providing recommendations: $5.0 \pm 0.5 \text{ t ha}^{-1}$. Abbreviations: *FP* farmers practice,

R FRG-2012 Nutrient recommendations as per FRG-2012, *G FRG-2012* Nutrient use gaps as per FRG-2012, *R FRG-2018* Nutrient recommendations as per FRG-2018 and *G FRG-2018* Nutrient use gaps as per FRG-2018

Northern China also, farmers who used high organic manure rates generally used lower rates of chemical fertilizer (Zhou et al. 2010). Moreover, during the FGD, the study found that large farms are unable to obtain a sufficient supply of organic manures on their own farms or in the local markets. Due to subsidized fertilizers, medium- and large-scale farmers are now becoming more dependent on chemical fertilizers for crop production (Miah et al. 2019). Some recent studies also reported a positive correlation between fertilizer use rates and farm size (Baral et al. 2020; Jahiruddin et al. 2010; Miah et al. 2019; Nasrin et al. 2019). More generally, Giller et al. (2021) report that for small-scale farmers across six countries in Africa, the capacity to invest more in modern technologies, like fertilizers, to close the current crop yield gaps is limited relative to large farms. However, the unique insights that we reported are as follows: (i) previous studies did not consider the full range of

recommended macronutrients and micronutrients applied; (ii) previous studies estimated gaps only for specific fertilizers (urea, triple superphosphate and muriate of potash) rather for all nutrient inputs; and (iii) the estimate of fertilizer use gaps in previous studies failed show how nutrient use gaps differ from crop to crop, or from small-scale farmers to large-scale farmers under diverse cropping patterns. In our study, we estimated farmers' nutrient use rates using diverse nutrient sources which is very rare in the literature. For example, in addition to chemical fertilizers (TSP, gypsum, MgSO_4 , and ZnSO_4), we accounted for remaining crop residue of the previous crop, cow-dung and poultry litter inputs as sources of S to estimate the farmers' current S use rates. More importantly, we developed an equation to estimate the farmers' current nutrient use that can be extended by adding other nutrient inputs like irrigation and rainfall in future research.

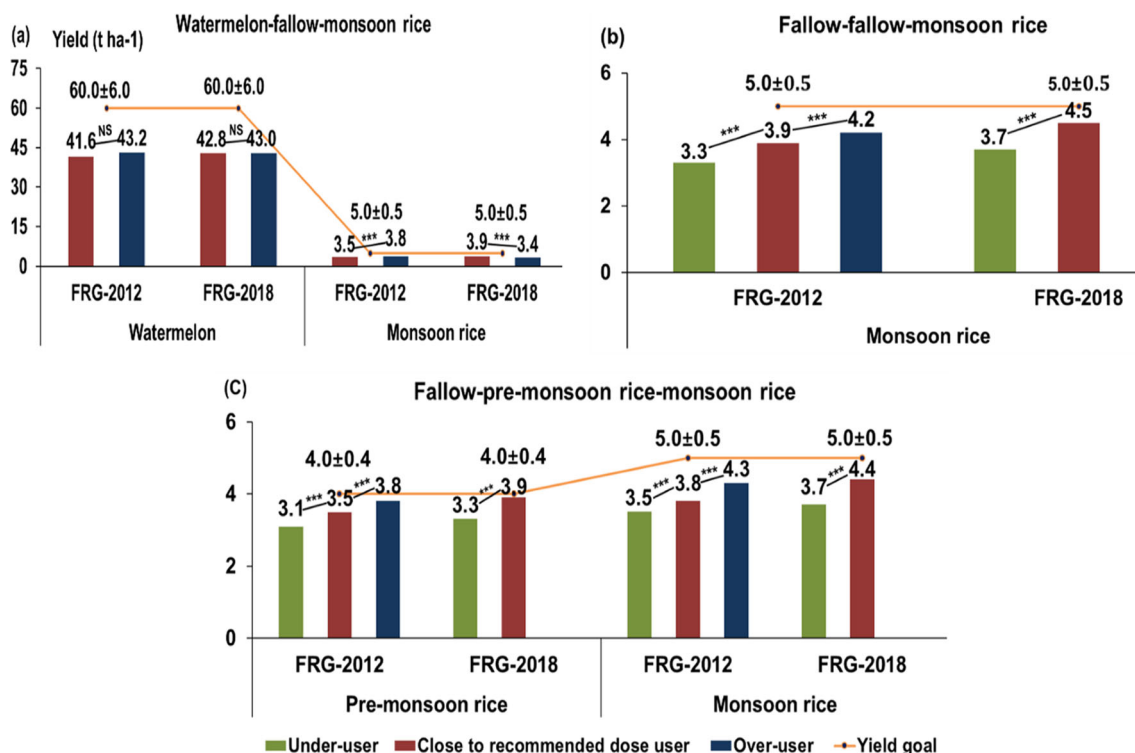


Fig. 7 Crop yields ($t\ ha^{-1}$) according to fertilizer use by farmers (categorized as over-user, close to recommended-dose user, under-user categories) relative to FRG-12 and FRG-18 recommendations. Except for watermelon, the result of the *t*-test (see Supplementary Table 4) confirmed that relative to newly released FRG-2018 recommendations

close to recommended dose user category farmers received statistically significant higher rice yield than the unbalanced nutrient user (over-user or under-user). ***, ** and * represents 1%, 5%, and 10% level of significance. NS represents non-significant

4.2 Fertilizer use and gaps relative to government-endorsed recommendations

A decade ago, farmers in the coastal saline AEZ-13 mostly used urea but very limited amounts of P- and K-containing fertilizers (Islam et al. 2008) that did not fully replace P and K removed in crop production due to less visible effects of these fertilizers on crops relative to N. This can be attributed to farmers' limited understanding about the importance of balanced use of nutrients and to the government fertilizer pricing policy which favored urea use (Huang et al. 2017). After that, the subsidy applied to P and K fertilizers greatly changed the NPK ratio from 10:1.5:1.3 in 2008–2009 to 10:4.6:2.8 in 2013–2014 in Bangladesh. Increased use of TSP, DAP, and MOP fertilizers due to the subsidy appears to have contributed to more balanced fertilizer use for rice crop especially by the small-scale farmers. Indeed, the increase in P fertilizer use in the last decade has built soil P levels to the point where the FRG 2018 recommendations proposed reduced P rates for monsoon rice cultivated after pre-monsoon rice and watermelon.

From FGDs, farmers reported that 'higher rates of P-containing fertilizer provides higher yield' which may explain the overdose of P in the saline-affected areas. Generally, crops take up only 15 to 25% of the total P applied in the season of

application and the rest remains unused in the soil (FRG 2018). Their reports indicate that farmers' prime concern was to enhance the crop yield rather than the economic use of nutrients. Moreover, DAP fertilizer use increased by almost 139% in fiscal years (FY) 2020–2021 from FY 2013 to 2014 in Bangladesh due to highly subsidized price (BER 2021). Increased use of DAP fertilizer relative to TSP might be another key reason for the recent increased use of P and decreased use of N in the study areas. If this type of subsidy scheme is not supervised efficiently, P overdosing could continually increase in the near future, which will not only be an inefficient use of Government investments but also could be a threat to water quality by increasing P export to waterways (Recous et al. 2019).

In the study area, farmers significantly underused K relative to the FRG-2012 and more so relative to FRG-2018, despite the subsidized price of K-containing fertilizers. The current subsidized price of K-containing fertilizer is lower per kilogram than the N fertilizer urea (Huang et al. 2017). Due to soil salinity, there may also be a misconception among farmers that K increases salinity damage, especially in rice crops. For example, farmers of the Barguna district perceived that the use of K in highland or medium highland could increase soil salinity which in turn, could hamper rice productivity. This is a challenge for extension programmes since K

Table 3 Financial loss (USD ha⁻¹) of the farmers and Government for using overdose of NPK nutrients under rice-based cropping patterns in the saline coastal zone of the Ganges Delta. Abbreviations: FRG Fertilizer recommendation Guide, MOP Muriate of potash, TSP Triple superphosphate

Fertilizer	Two fully rice-based cropping pattern						Cropping pattern with high-value watermelon crop					
	Farmers' loss		Govt. loss		Farmers' loss		Govt. loss		Farmers' loss		Govt. loss	
	as per FRG- 2012	as per FRG- 2018	as per FRG- 2012	as per FRG- 2018	as per FRG- 2012	as per FRG- 2018	as per FRG- 2012	as per FRG- 2018	as per FRG- 2012	as per FRG- 2018	as per FRG- 2012	as per FRG- 2018
a. Large-scale farmers												
Urea	15.0	13.1	13.1		420.5	79.2	69.3	69.3	344.6	64.9	56.8	56.8
TSP	34.4	78.2	108	28.0	137.5	35.6	80.9	80.9	132.5	34.3	77.9	77.9
MOP	6.4	11.6			32.0	5.6	10.2	10.2				
Total loss (USD ha ⁻¹)	55.8	102.9		28.0	63.5	120.4	160.3	160.3		99.2	134.7	134.7
b. Medium-scale farmers												
Urea	12.8	11.2			371.07	69.8	61.1	61.1	295.1	55.6	48.6	48.6
TSP	29.5	67.1	89	23.0	117.5	30.4	69.1	69.1	112.5	29.1	66.2	66.2
MOP	1.4	2.5			20.2	3.6	6.4	6.4				
Total loss (USD ha ⁻¹)	43.7	80.8		23.0	52.4	103.8	136.7	136.7		84.7	114.8	114.8
c. Small-scale farmers												
Urea	2.6	2.3			315.08	59.3	51.9	51.9	239.1	45.0	39.4	39.4
TSP	17.6	40.0	43	11.1	60.50	15.7	35.6	35.6	55.5	14.4	32.6	32.6
MOP	0.0	0.0			2.60	0.5	0.8	0.8				
Total loss (USD ha ⁻¹)	20.2	42.3		11.1	25.3	75.4	88.3	88.3		59.4	72.0	72.0
d. All categories												
Urea	10.1	8.8			368.9	69.4	60.8	60.8	293.0	55.1	48.3	48.3
TSP	27.2	61.8	80	20.7	105	27.2	61.8	61.8	100.0	25.9	58.8	58.8
MOP	1.8	3.2			18.2	3.2	5.8	5.8				
Total loss (USD ha ⁻¹)	39.1	73.8		11.1	25.3	99.8	128.3	128.3		81.0	107.1	107.1

(Authors own calculation based on survey result)

(1USD \$)=85 Taka)

**Conversion factor: urea= kg N × 2.17, TSP= kg P × 5.0 and MoP= kg K × 2.0 (FRG 2012)

Maximum retail price (fixed by the Govt.) per kg of fertilizer (with subsidy) for farmers: Urea = \$ 0.19, TSP= \$ 0.26 and MoP= \$ 0.18

Dealer purchase price (fixed by the Govt. of Bangladesh) per kg of fertilizer (with subsidy): Urea = \$ 0.16, TSP= \$ 0.24 and MoP= \$ 0.15

Govt. procurement price of per kg fertilizer (for imported fertilizers): Urea = \$ 0.33, TSP= \$ 0.82 and MoP= \$ 0.47

Govt. subsidy of per kg fertilizer (for imported fertilizers): Urea = \$ 0.16, TSP= \$ 0.59 and MoP= \$ 0.32

Source: Ministry of Agriculture, Bangladesh, and Bangladesh Chemical Industries Corporation (BCIC), July 2021

applied at the recommended rate increases crop tolerance to salinity rather than exacerbating it (Jan et al. 2017). While the K:N ratio showed an upward trend in Bangladesh it was still far below crop requirements and soil test results (Hossain and Siddique 2020). Since FRG-2018 has increased the K rate recommendation for saline soil of the coastal zone of Bangladesh due to K deficiency in the soil, a systematic extension programme may be needed to demonstrate to farmers the benefits of recommended rates of K fertilizer.

Despite the low use of S-containing fertilizers, there was limited underdosing of S by farmers in the saline coastal zone. Due to the medium to optimum level S status of soil, S recommendation is low for AEZ-13 (FRG-2012 and FRG-2018). Moreover, crops acquire S from multiple sources. Even S content in rainfall water that increased from 3 in 1993 to 4–5 mg L⁻¹ in 2009 in Bangladesh due to industrialization and urbanization (Haque et al. 2015) might be a significant source of S, especially for monsoon rice (Bell 2008). For those reasons, farmers might not observe any S deficiency symptoms in crops, or confuse them with N deficiency symptoms, which could be another reason for underdose of S used in SCR of Bangladesh.

For all categories of farmers, Zn and B use rates were under the recommended dose levels. In Bangladesh, farmers are generally unaware of the importance of micronutrients (Hossain and Siddique 2020). Furthermore, the prices of micronutrients per unit weight are relatively high and do not attract subsidies. The state governments of India have promoted micronutrient use on land with deficiencies by instituting a 50% subsidy for three micronutrients (Kishore et al. 2021). A similar scheme in Bangladesh may promote more effective use of micronutrients, but first, quality assurance of micronutrient products needs to be implemented since at present market surveys suggest that a large proportion of Zn products supply much less than the certified value (SRDI 2019). From the FGD, it was apparent that financially solvent farmers who maintained close contact with the government extension workers most commonly used Zn and B in crops in the saline coastal zone. As extension facilities are more accessible to medium- and large-scale farmers (Afrad et al. 2019), the underdoses of micronutrients by the small-scale farmers may reflect a lack of information access from extension sources. Our study is the first to identify a B use gap by farmers for watermelon in the saline-affected areas.

4.3 Farmers' investment on fertilizer, crop yield, and sustainable intensification

A baseline survey by Miah et al. (2019) reported that on farms of SCRB, pre-monsoon rice is not profitable (benefit-cost ratio (BCR) is 0.99) because of low yield, high production cost, and low market price which appeared to explain why small-scale farmers of SCRB are less likely to invest in fertilizer for rice crops. Due to crop yield reduction or crop damage from soil

salinity, strong wind, cyclone, etc., credit-constrained small-scale farmers in the FGD opined that it was difficult to recover the cost of investment in rice crops which in turn increased negative preference for fertilizer use, but such considerations were less significant for more wealthy farmers (Khor et al. 2018). Many studies indicate that credit support to small-scale farmers' increases fertilizer use intensity (e.g. Ouattara et al. 2020), but without ensuring balanced fertilizer use, it could add to the financial burden of the credit receivers if there is not a profitable return on investment. Bhattacharya et al. (2019) reported that small-scale farmers can only obtain a higher yield (up to 4.6 and 5.3 t ha⁻¹, respectively) and profitable BCR (1.12 and 1.25, respectively) for pre-monsoon rice and monsoon rice if they used balanced fertilizers and practiced other recommended agronomic management practices. Similarly, experimental evidence from WCRI showed that balanced fertilizer increased monsoon rice yield (by 36%) and BCR compared to the outcomes for farmers' who used unbalanced fertilizer (Mandal et al. 2020). So, with the widespread use of balanced nutrients, it is feasible to increase crop yield as well as cropping intensity of small-scale farmers, which could enhance food security for over 50 million people of the Ganges Delta.

For the high-value watermelon crop, farmers, regardless of farm size, made different decisions to those for rice. The application of higher-than-recommended N and P rates of fertilizer for watermelon even by small-scale farms suggests that regardless of financial constraints, for high-value crops, farmers are motivated by profit seeking to put aside their negative preferences for investment in fertilizer (Aravindakshan et al. 2021; Mandal et al. 2020). Farmers reported in the FGD that they used high overdose of N and P in watermelon for fast vegetative growth so that they can sell fruit early in the market which attracts higher prices from the buyers. Despite financial constraints, small-scale farms also choose to use high overdose of N and P, like the medium- and large-scale farms, to get the benefit of early sales. Moreover, during FGD, the study found that watermelon farmers, regardless of size, can easily buy fertilizers on credit from the local fertilizer dealers who are confident of repayment of the credit just after harvest of the watermelon. Since watermelon provides a better return in the SCRB (BCR of 1.75), farmers were more likely to invest in subsidized fertilizer to maximize crop yield (Miah et al. 2019). Like watermelon farmers of SCRB, potato farmers in WCRI spend twice as much on fertilizer to cultivate high-value potatoes relative to the money required for balanced fertilization based on field experiments (Mandal et al. 2020). In parts of Sub-Saharan African and China, farmers are now applying relatively more fertilizer in profit-potential crops (Miao et al. 2011; Olaleye and Edje 2020). For example, nutrient input rates in the cash crops were around 60% higher than those in the cereal crops in China which mostly occurred in the economically developed coastal provinces (Miao et al. 2011).

Studies suggest that farmers overapply nutrients if the recommended rate is perceived to be too conservative and that profits can be maximized by using more nutrients than the recommended rates (Sheriff 2005). The result suggests that the yield gap from using unbalanced nutrients on watermelon and monsoon rice (23 and 2.0 t ha⁻¹, respectively) in the watermelon-monsoon rice cropping pattern is still wide relative to the attainable yield reported in the FRG (2018). Similar to the SCRB, a large yield gap was found for high-value potato farmers (4.02 t ha⁻¹ between farmers' field and experimental plot) in the WCRI due to unbalanced fertilizer use practices (Mandal et al. 2020). This suggests that despite the prevalence of fertilizer overdosing for high-value crops, farmers are failing to realise the benefits of higher yield potential and profitability of these crops.

4.4 Residual value of nutrients and farmers' perceptions

During FGD, the study found that farmers perceived that some of the fertilizer applied to watermelon would remain available to the following rice crop, and those residual nutrients would supply sufficient nutrients to monsoon rice while minimizing the cost of production for rice. Since watermelon vines were removed from the field or used in the household as animal feed and fuel and farmers preferred to use limited cow-dung or poultry litter in wet soil (see Supplementary Table 1), nutrient sources were limited for monsoon rice. On the other hand, nutrient use rates in monsoon rice were relatively higher under the *fallow-fallow-monsoon rice* cropping pattern as there was less scope for the single monsoon rice crop to acquire residual nutrients from those supplied to previous crops. Nutrient adjustment between two crops within the same cropping patterns is a very common practice in Bangladesh since the high profit-potential crop gets preference (Ali et al. 2009). Waddington et al. (2018) reported a similar nutrient use pattern and cost adjusting tendency in the potato-maize cropping pattern in northern Bangladesh. The FRG (2018) also endorses the decrease in recommended crop-based fertilizer rates when considering the annual cropping pattern, based on the residual value of P and K, but there appears to be little experimental evidence reported to validate the residual value of fertilizers in SCRB.

Current recommendations assume that more than 60% of added N is lost in different ways and very little or no residue is left for the subsequent crop (FRG 2018). Recent work in Bangladesh suggests that 15–20% of N added as urea is lost as ammonia (Uddin et al. 2020), but there is limited information on ammonia losses in cropping patterns more generally or other N loss pathways. Hence, N is recommended at full dose in the FRG-2018 regardless of the previous crop application rate. By contrast, in the FRG-2018, for pattern-based recommendations rates of P, K, S, Zn, and B, could be reduced by

30–50% for subsequent crops depending on the types of crop, cropping season, and number of crops cultivated in the cropping year. Farmers' current practices of using high overdose of nutrients in one crop and high underdose of nutrients like N which has no or little residual effect on the subsequent crop are contrary to pattern-based recommendations given by FRG-2018. Our result indicated that yield gap of monsoon rice under watermelon-monsoon rice pattern was higher than that of monsoon rice cultivated in the other rice-based pattern. However, experimental evidence or whole-farm data regarding the impact of such nutrient use choices by farmers on annual farm profit are needed to conclude whether the farmers' choice is the most rational one.

4.5 Overuse of subsidized fertilizers and financial and environment loss

In south Asian countries, NPK-containing fertilizers are highly subsidized (Kishore et al. 2021). However, the current universal subsidy schemes especially in Bangladesh appears to provide more benefit to certain categories of farmers, crops, and regions (Barkat et al. 2010; Miah et al. 2019; Nasrin et al. 2019). For example, medium- and large-scale farmers enjoy 1.6 and 1.1 times more fertilizer subsidy relative to small-scale farmers using their higher purchasing capability (Nasrin et al. 2018). Although the Government of Bangladesh allocated around US\$ 823.5 million to subsidize fertilizer use in the fiscal year 2020–2021 (Parvez 2020), about 72% of marginal farmers were not aware of the magnitude of the Government investment (Nasrin et al. 2019). According to the Ministry of Agriculture, Bangladesh, the Government has reduced the DAP fertilizer price from Tk. 25 per kilogram to Tk. 16 per kilogram from 16 December 2019 onwards, despite an existing subsidy for DAP fertilizer. The Government allocated an additional \$ 94.4 million to extend the DAP subsidy (BSS 2019). High fertilizer subsidy may increase fertilizer use, but it does not ensure balanced use of fertilizer (Huang et al. 2017). Indeed, the overuse of fertilizers especially in high-value crops could impose an extra financial burden on both the farmers and the governments of the Ganges Delta that ultimately could hinder the achievement of the SDGs. Apart from our study, there is limited evidence regarding how much treasuries the governments of the Ganges Delta are losing due to overuse of subsidized fertilizers by the farmers.

Like financial losses, environmental degradation could be controlled through the widespread adoption of recommended nutrient use practices. For example, the apparent recovery efficiency of N (AR_n) could increase for maize from 16.2 to 30.2% if P is used along with N and could increase up to 32% if PK is used along with N (Prasad 2013). For wheat, AR_n could increase up to 64% if NPK is used in a balanced form (Prasad 2013). In addition, recommended nutrient use practice increases the nutrient uptake capacity of rice crops (Bora et al.

2018). Only 1% increase of N use efficiency through balanced fertilizer use practices could save 0.4 million tonnes of urea in India (Prasad 2013) that could reduce atmospheric and leaching loss of N which ultimately could decrease environmental degradation dramatically.

5 Conclusions

Currently, 66–82% of farmers of the saline coastal zone of the Ganges Delta are using overdoses or underdoses of nutrients relative to government-endorsed recommendations but the gaps vary among different crops, cropping patterns, and farm size. Small-scale farms used lower rates of nutrients relative to medium- and large-scale farms due to financial insolvency, lack of credit access, lack of extension and information access, and, for rice crops, a tendency to risk-adverse behaviour. Nevertheless, the small-scale farms, like the medium- and large-scale farms, applied overdoses of N and P fertilizer for the highly profitable watermelon. Extension workers need to be focused more on increasing N, K, Zn, and B use on rice, especially by the small-scale farms, and to decrease P use, especially by the large- and medium-scale farms in the saline areas. For high-value crops like watermelon, there is an opportunity to lower production costs by minimizing the current farmers' practice of using excessive fertilizer. While fertilizer recommendation guides are useful they need to be communicated to all categories of farmers so they can acquire confidence in them and ascertain the benefits of using FRG-based recommended nutrients. Moreover, it is essential to differentiate the nutrient use gaps among farm sizes and cropping patterns to take appropriate measures for controlling the overuse or underuse of recommended nutrients to achieve profitable crop yield and farm profitability.

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Data availability All data analysed during this study are included in the published article and its supplementary information files.

Code availability Not applicable

Declarations

Conflicts of interest The authors declare no competing interests.

Ethics approval/declarations The authors declare that the approval of the Ethical Review Board from Murdoch University Australia was taken.

Consent to participate The authors confirm that the verbal consent of the respondents to participate in the interviews was taken during fieldwork.

Consent for publication The authors confirm that verbal consent for publication of aggregate data was taken without disclosing participant names.

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