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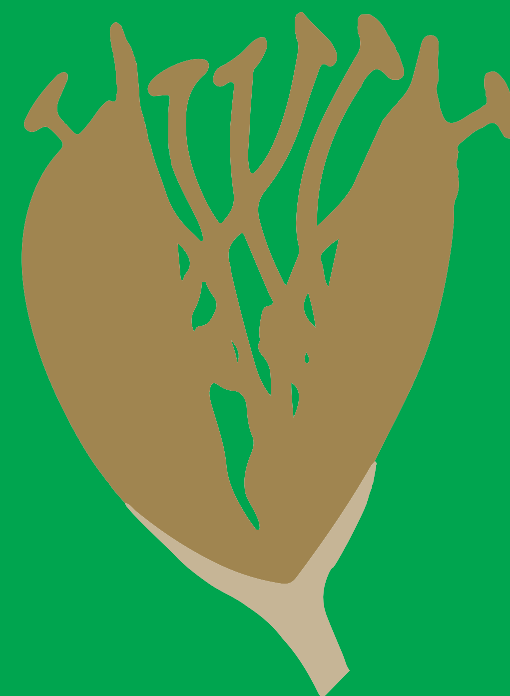
Doubling Rice Productivity



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Doubling Rice Productivity in Bangladesh: A Way to Achieving SDG 2 and Moving Forward

M S Kabir[1*], M U Salam[2*], A K M S Islam[3], M A R Sarkar[4], M A A Mamun[5], M C Rahman[4], B Nessa[6], M J Kabir[4], H B Shozib[7], M B Hossain[8], A Chowdhury[4], M Nasim[9], K M Iftekharuddaula[10], M S Hossain[11], M K A Bhuiyan[12], B Karmakar[13], M S Rahman[14], M M Haque[15], M T Khatun[6], M P Ali[16], S M H A Rabbi[17], P L Biswas[18], E S M H Rashid[19] and N M F Rahman[5]

ABSTRACT

Built on deep-rooted political and cultural heritage, 'rice security' is the foundation of 'food security' in Bangladesh. The country has been in production-surplus of rice in the current decade feeding over 165 million people. This on-going 'self-sufficiency momentum' would require to maintain to meet increased demand from growing future population. On developmental side, Bangladesh is placed among the three of the world's fastest growing economies in the years through to 2050. Rice sector would need to match with the pace of this growth. In addition, agriculture sector, that includes rice, is to double the productivity as the government commits to meet the SDG goal 2.3.1. This study addresses those issues through scoping increased rice production and productivity in Bangladesh, developing a plan of work (POW) on translating the scope and designing implementation plans and actions, incorporating efficiency, resilience, stability and sustainability issues, to achieve the POW. The study has used brainstorming, and rigorous analysis to achieve the objectives. The productivity has been explained in terms of yield- and labour-productivity. The developed three-winged 'doubling rice productivity (DRP)' framework directs yield enhancement and production accumulation in unexplored spaces (Wing-1); increased adoption of mechanization to impact on labour productivity (Wing-2), and improvements in nutritional quality and rice-based product diversity, and stabilizing the farmgate price (Wing-3). Analyses show, from the baseline figure of 35.29 MT in 2015, rice production in the country can be raised to 46.90 MT in 2030, 54.09 MT in 2040 and 60.85 MT in 2050 with combined contributions of three pillars – yield improvements by enhanced varietal potential (Pillar 1), reduction in existing yield gap (Pillar 2) and production increase by exploring unexplored spaces for rice (Pillar 3) of Wing-1 of the DRP. This production will produce a surplus of 6.50, 10.29 and 13.65 MT in 2030, 2040 and 2050, respectively, over the production target (40.40, 43.80 and 47.20 MT in 2030 and 2050, respectively). Results further reveal that through scale-appropriate mechanization backed up by estimated fair price, labour productivity in rice will be doubled by 2029, meeting the SDG 2.3.1. Good number of released varieties have been identified to have specific nutritional trait, and value adding quality. We have emphasized on much needed actions on demand-driven research for varietal development and field-adoptable management, mechanization for transplanting and harvesting operations, accommodation of rice in unexplored spaces, farmer-based speedy seed multiplication and dissemination system, establishment of commission for agricultural costs and prices, input buffer stock terminals for managing production risk, long-term storage and export of surplus production, and research-publicity-market development for rice-based products through public-private partnership. It is concluded that efficiency, resilience and sustainability around the three wings of DRP in the rice production systems to be ensured to achieve the rice production, productivity and labour use estimates.

Key words: Genetic potential, labour productivity, management potential, mechanization, diffusion-adoption model, space potential, sustainability, yield loss.

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INTRODUCTION

Bangladesh will emerge as the 28th largest economy of the world by 2030 and 23rd by 2050, predicts PricewaterhouseCoopers, a leading global accounting firm (PwC, 2017). The firm further projects, the country will be among the three (after Vietnam and India) of the world's fastest growing economies over the period of 2016-2050. If this happens, and should happen, agriculture will face extra pressure for producing increased food for growing population in the backdrop of diverting resources from this sector to fast-growing non-agriculture sectors. The solution to the challenges is to be the increasing agricultural production efficiency and sustainability.

Bangladesh has been transforming from a traditional agriculture-dominant economy to a modern industrial-based economy (WB, 2007). In such transformation, according to 'structural theory[2]', it is essential that agriculture sector modernizes itself ensuring improved productivity (Adelman, 1984). Productivity is defined here as the output of valued product per unit of resource input (Conway, 1987). There are three basic resource inputs in agriculture – land, labour, and capital. Therefore, measures of productivity could be against any of those resource inputs or their components. For rice, as in other crops, the productivity is usually expressed as yield per hectare (considering land-resource input; henceforth we denote it as 'land productivity'); but under circumstances, it can be viewed as yield per labour unit (considering labour-resource input; henceforth we denote it as 'labour productivity').

According to Miah *et al*. (2020), enhancing labour productivity in agriculture is critical for two aspects: (i) it increases the demand for modern agricultural machinery and tools (*sink*), and (ii) it releases agricultural labour force to be absorbed in industry (*source*). The much-needed industrialization of Bangladesh's developing economy will be highly unlikely without laying a solid foundation of agriculture through increased production and productivity.

Rice is the backbone of Bangladesh's agriculture; here, like in many other countries, 'food security' almost entirely depends on 'rice security' (Brolley, 2015); it alone contributes about 4.5% to the GDP (BBS, 2020). The crop, both politically- and culturally-sensitive, occupies about 78% of annual agricultural land (gross cropped area), and currently in production-surplus feeding ~165 million people (Kabir *et al*., 2015). The increasing population will demand more rice production in future (although per capita rice consumption is gradually declining), while the continuity of the on-going 'self-sufficiency momentum' will depend on the outcome of land-, labour- and system- productivity. The country will need to increase land productivity because the current production environment will change in future encountering decreasing crop land and labour resources, and increasing climate vulnerability. Side by side, it will also be needed to double the labour productivity as a requirement to meet the SDG 2.3.1, where scale-appropriate mechanization backed up by fair price is to play a crucial role. It may be noted that the government of Bangladesh is fully committed in meeting sustainable development agenda to be a part of 'leave no one behind'.

Stability and sustainability are the two components of production systems that needed to address into productivity in order to ensure

[2] Relative weight of significant components of the aggregative indicators of the economy, such as GDP and labour force, by which growth brings about in the economy, which is brought about by resources being transferred between sectors in the economy in response to the changing pattern of consumer demand, technological development and differential rates of productivity growth (more details in Gali *et al*., 2000).

resilience. As described by Conway (1987), stability is the constancy of productivity in the face of small disturbing forces arising from the normal fluctuations and cycles in the surrounding physical, biological, social and economic environments, such as fluctuations in the climate or in the market demand. Sustainability, on the other hand, is the ability of an agroecosystem to maintain productivity at least equal to or higher compared to long term (3-5 years or even 10-20 years) average yield (Lynam and Herdt, 1989) when subjected to a major disturbing force, such as salinity, erosion, indebtedness, declining market demand, rare drought or flood or what the world is facing now, the zoonotic disease COVID-19.

Considering the food habit of the people of Bangladesh, 'rice security' should also address the 'nutrition security'. In this country, rice is not only the carbohydrate-supplying food, but also the major provider of protein, micronutrients, and health benefits. Antioxidants supplied by rice contribute to relieving oxidative stress, and preventing cancer, cardiovascular problems and complications of diabetes (Shozib *et al.*, 2020). In addition to contribution to nutrition security, rice as a commodity could be attractive to consumers beyond its traditional use of 'cooked rice'. Emphasizing research and marketing on rice-based products would boost the morale of stakeholders in increasing rice production and productivity of Bangladesh.

With the above background, this paper aims to present the:

- scope of increasing land- and labour-productivity in the rice sector in Bangladesh to meet the SDG 2.3.1 and taking the momentum further beyond;
- plan of work (POW), translating the scope; and,
- implementation plans and actions to achieve the POW for improving efficiency and sustainability of rice farming.

METHODOLOGY

Study Approach

Analysis and synthesis underlying historical, current and future production and/or productivity of rice accounted for this study followed in three dimensions: vertical, horizontal and cross-dimensional. The vertical dimension included yield improvements by enhanced genetic potential (GenPot), and reduction in existing yield loss through every aspect of crop management (ManPot). The horizontal dimension addressed production increase by exploring unexplored spaces for rice (SpacePot), and speeding up the adoption cycle of promising varieties. The farm mechanization, and rice market price risk were analyzed across cross-dimensional aspects. In addition, the study addressed the issues of nutritional improvements, future production and productivity challenges, and highlighted evidence-based successes encountering production environments including those caused by climate change.

The Concept of Doubling Rice Productivity (DRP) Framework

Ten brainstorming sessions were conducted with the participation of 25 professionals representing national and international rice scientists and senior rice research managers. The first session accumulated all the possible components and sub-components of the concept of the Doubling Rice Productivity (DRP) framework, including the terminologies to be used in the study. Further, discussion included the right definitions of terminologies to be used for the DRP framework. In the second session, a draft of the DRP framework was developed through group discussion. The draft was sent to each of the participants for thorough scrutiny and comments. In the third and final session, the draft DRP framework was finalized by addressing the comments. Each session lasted for about three hours.

There is a general perception that 'doubling productivity' denotes for 'double the production'. According to the meta data definition of SDG (https://www.sdg.gov.bd/public/files/upload/IndicatorMetadataFiles/5e686b8e0245e_320_Metadata-02-03-01.pdf), the 'doubling productivity' is expressed as 'doubling labour productivity', which can be achieved through increased production and reduced labour use. In this study, we have adopted 'Doubling Rice Productivity (DRP)'as a concept for sustaining rice production against all the odds. We define DRP as *systematic approach for the improvements of rice production system, which will result in incremental progression of yield, expansion of rice area in unexplored lands, widespread adoption of mechanization, enrichment of product quality, ensured fair price, and minimizing risks.* Taken all together, DRP inherently will double the rice labour productivity. Here, rice labour productivity is expressed as 'rice labour productivity index', which is an output of DRP.

Measurement of Rice Productivity, Production and Sensitivity

Annual rice productivity and production were calculated for the period of 2015 through 2050.

Estimation of varietal yield potential

$$\mathrm{VYP_a} = \mathrm{RPTCYL_a} \times \mathrm{RA_a}^{-1} \ldots\ldots \mathrm{Eq.\,1}$$

Where VYP_a is variety yield potential (t ha^{-1}), annualized across the varieties and rice growing seasons; RA_a is the total area under rice in a given year considering all rice growing seasons (million hectare); and $RPTCYL_a$ is the annual rice production target (million ton) assuming yield loss will remain at the same percentage in future as of the current level. Data for RA_a were sourced from published document which accounted for declining rice area (Kabir *et al*., 2015). $RPTCYL_a$ was calculated as follows:

$$\mathrm{RPTCYL_a} = \mathrm{RPT_a} \times (1 - \mathrm{YL})^{-1} \ldots\ldots \mathrm{Eq.\,2}$$

Where, RPT_a is the annual rice production target (million ton); YL is the annualized yield loss (expressed as fraction). Data for RPT_a were sourced from published document (Kabir *et al*., 2015). YL was calculated in the following section 'Estimation of yield loss and creation of yield loss minimization scenario'.

Estimation of yield loss and creation of yield loss minimization scenario

The term 'yield loss' is defined here as the 'gap' between potential farm yield and actual farm yield, expressed as percentage of potential farm yield. The loss was previously estimated for rice by the Bangladesh Rice Research Institute (BRRI) as 20.7% considering yields of major varieties in the research fields and national yields during 2009-2013 (Kabir *et al*., 2015). This loss is related to crop management. BRRI in its earlier study, did not partition the yield loss by management components. For the requirement of this study, the overall yield loss estimated by BRRI (20.70%) partitioned into 14 components using three tools – literature search, brainstorming and expert consultation. The management component specific collated yield loss figures from literature were discussed, debated and compiled in 12 brainstorming sessions participated by 25 multidisciplinary rice experts of national and international repute. The management component-wise yield loss table was sent to senior scientists of respective disciplines for their comments and observations. Finally, the management component-wise yield loss figures were finalized by rigorous discussion on the comments and observations with selected 25 multidisciplinary rice scientists.

The yield loss minimization scenario was analyzed using the following equation:

$$\mathrm{YL_{cy}} = \mathrm{YL_{py}} - \left(\mathrm{YL_{py}} \times \left({}^{\mathrm{YL_{mc}}}/_{100}\right)\right) \ldots\ldots \mathrm{Eq.\,3}$$

Where, YL_{cy} is the yield loss in current year (%), YL_{py} is the yield loss in previous year (%) and YL_{mc} is the yield loss minimization constant; this constant was assumed as 3 (% per year) aiming the yield loss reduced to around 7% in 2050 from the baseline figure of 20.61%.

Estimation of production in the unexplored spaces

Based on current land utilization status and rice cropping suitability, five spaces were identified through 'expert consultation'. They are: (i) Space 1: Greater Barishal region; (ii) Space 2: North-eastern Bangladesh predominantly greater Sylhet region; (iii) Space 3: South-west and greater Jashore region; (iv) Space 4: Coastal charland in greater Barishal region and Noakhali district; and (v) Space 5: Chattogram hill tracts especially Kaptai lake areas.

On a five-year time-step (beginning at 2020 through to 2050), rice area and yield for each space were estimated by 'expert consultation'. Space-wise rice production (million ton) for each time-step was calculated by multiplying yield by area.

The production was estimated by regressing the rate of total production (million ton) of the five unexplored spaces over seven time-steps, as depicted in the following equation:

$$Y = \alpha + \beta t \ldots\ldots \text{Eq. } 4$$

Where, Y is the total production (million ton) of the five unexplored spaces (SpacePot) and t is the year from 2020 to 2050. The estimated coefficient for α and β was -25.2706 and 0.012841, respectively.

Estimation of production flow and production targets

The total production of rice (million ton) in a given year was calculated as the sum of production contribution improved genetic potential, yield gap minimization, and cropping in the unexplored area (described in Section 'Estimation of production in the unexplored spaces').

The production contribution improved genetic potential was estimated using the following equation:

$$PC_{igp} = RPTCYL_a - PL_{yl} \ldots\ldots \text{Eq. } 5$$

Where, PC_{igp} is the production contribution from improved genetic potential; and $RPTCYL_a$ is the annual rice production target (million ton) assuming yield loss will remain at the same percentage in future as of the current level [Eq. 2]; and PL_{yl} is the production loss due to yield loss (million ton), calculated as follows:

$$PL_{yl} = RPTCYL_a \times \left({}^{YL}/_{100} \right) \ldots\ldots \text{Eq. } 6$$

Where, $RPTCYL_a$ is the annual rice production target (million ton) assuming yield loss will remain at the same percentage in future as of the current level [Eq. 2]; and YL is the annualized yield loss (expressed as fraction), the value estimated in the study (Section 'Estimation of yield loss and creation of yield loss minimization scenario').

The production contribution from yield loss minimization (PC_{ylm}) was estimated using the following equation:

$$PC_{ylm} = PL_{yl} - RPTCYL_a \times \left({}^{YG_{cy}}/_{100} \right) \ldots\ldots \text{Eq. } 7$$

Where, PL_{yl} derived from Eq. 6; $RPTCYL_a$ from Eq. 2 and YL_{cy} from Eq. 3.

The production contribution from production gain from unexplored space (PC_{gua}) was estimated by regressing total production (million ton) of the five unexplored spaces (Section 'Estimation of production in the unexplored spaces') over seven time-steps (2020, 2025, 2030, 2035, 2040, 2045 and 2050), as depicted in the following best-fitted third-order polynomial equation:

$$PC_{gua} = \alpha + \beta_1 t + \beta_2 t^2 + \beta_3 t^3) \ldots\ldots \text{Eq. } 8$$

Where, the estimated coefficient for α, β_1, β_2 and β_3 was 0, 2.074274737, -0.002122457 and 0.00000054, respectively.

Two target production was set based on assumptions: (i) production will be driven by improved genetic potential, while no contribution from yield loss minimization and gain from unexplored space; and (ii) production will be driven simultaneously by improved genetic potential, yield loss minimization and gain from unexplored space.

Demand domain of production flow

The total rice demand was estimated by accounting human and non-human consumption requirements per annum in Bangladesh. The human consumption demand is the sum of per capita annual requirement of the total population of the country. The non-human consumption demand is the sum of the need for seed, feed, industrial use, and wastage for harvest operation, post-harvest losses, and processing losses per annum. The total rice demand was estimated based on the equations below:

$$TRD_i = HC_i + NHC_i \ldots\ldots \text{Eq. 9}$$

$$\mathrm{HC_i = PoP_i \times (CR + PR + FR + PoR + RC)} \ldots\ldots \text{Eq. 10}$$

$$NHC_i = S_i + F_i + \mathrm{IU}_i + \mathrm{HL}_i + \mathrm{PHL}_i + \mathrm{PL}_i \ldots\ldots \text{Eq. 11}$$

Where, TRD_i is the total rice demand for ith year; HC_i is the human consumption for ith year; NHC_i is the non-human consumption for ith year; PoP_i is population for ith year; CR_i is per capita clean rice consumption for ith year; PR_i is per capita puffed rice consumption for ith year; FR_i is per capita flattened rice consumption for ith year; PoR_i is per capita popped rice consumption for ith year; RC_i is per capita rice cake consumption for ith year; S_i is seed requirement for ith year; F_i is feed demand for ith year; IU_i is industrial use for ith year; HL_i is wastage for harvest operation for ith year; PHL_i is post-harvest losses for ith year and, PL_i is processing losses for ith year; where, i = 1, 2, 3 …nth year.

Data, which included decreasing trend in per capita rice consumption, were sourced from Kabir *et al*. (2015) and, estimated through to 2050 using the linear equation model.

Estimation of labour productivity

A rice labour productivity framework was developed accounting for area, production, price, and farm power (Fig. 1). The estimation of labour productivity in rice cropping considered five parameters on an annual-step: (i) country's total labour force, (ii) proportion of agricultural labour, (iii) proportion of rice labour, (iv) rice production target including safety net, and (v) rice market price. Data of total labour force sourced from literature and, as required, estimated through to 2050 using standard statistical procedures (Eq. 15). When data were not available, assumptions were made based on 'expert opinion'.

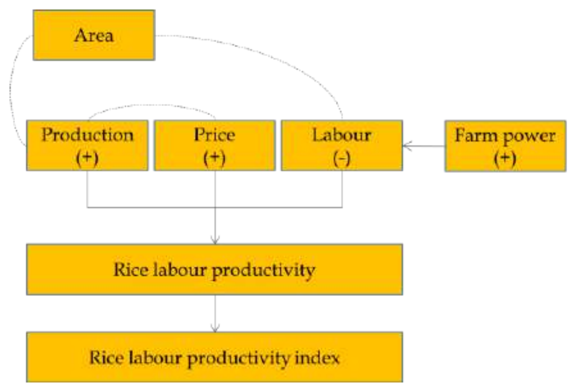


Fig. 1. A framework for increasing rice labour productivity in Bangladesh. The signs '+' and '−' denotes for the factors contributing positively and negatively, respectively, to the productivity. The solid and dotted lines represent direct and indirect effect in the system, respectively.

The labour productivity was estimated using the following equation:

$$\mathrm{RLP_d = ReRLP_d \times RP \times DWH} \ldots\ldots \text{Eq. 12}$$

Where, RLP_d is rice labour productivity as BDT labour^{-1} day^{-1}; $ReRLP_d$ is the rice equivalent RLP as kg labour^{-1} day^{-1}; RP is price of rice as BDT

kg^{-1}; and DWH is the daily work hour. The value of DWH was set as 8 in the line of daily standard work hours. The base value of RP was used as 32 BDT kg^{-1} as of 2015 market price with incremental increase @3% $year^{-1}$ in the subsequent years by adjusting inflation. The incremental values were estimated using data from 1991-2017 (FAOSTAT: http://www.fao.org/faostat/en/#data/PP). The $ReRLP_d$ was calculated using the following equation:

$$ReRLP_d = \left({}^{RPT_{aasn}}/_{RL_{av}} \right) \times CF \ldots\ldots Eq. 13$$

Where, RPT_{aasn} is the RPT_a (the annual rice production target in million ton; sourced from Kabir *et al.*, 2015, see Eq. 2) adjusted by adding 0.6 MT $year^{-1}$ as safety net; RL_{av} is the annual available rice labour (million by number); and CF is the conversion factor for adjusting ton to kilogram and year to day. The RL_{av} was calculated using the following equation:

$$RL_{av} = TaLF \times PrALF \times PrRLF \ldots\ldots Eq. 14$$

Where, TaLF is the total annual labour force (million by number); PrALF is the proportion of TaLF available for agricultural production; and PrRLF is the proportion of PrALF available for rice production, assumed as 60% (expert opinion). The TaLF was estimated using ILO data for the period of 2000 – 2017 (ILO, 2020) and projecting through to 2050 using the following linear equation for the years 2018 – 2050:

$$TaLF = \alpha + \beta t \ldots\ldots Eq. 15$$

Where, 't' is the time expressed as year. The estimated coefficient for α and β was -2105.16698 and 1.076708911, respectively.

The productivity index was expressed as the ratio of RLP_d of the base year (2015) to the RLP_d of the forwarding years through to 2020. The clean rice price and farm power availability were regressed on the years of the study period (2015 – 2050). The data of farm power availability were analyzed through an exponential equation using data from the literature (Mottaleb and Krupnik, 2015; MOA, 2016; Ahmmed, 2017; Islam, 2018; Alam, 2019).

Sensitivity analysis – the approach and execution

The composition of future rice production in Bangladesh is presented in the study by accounting for three pillars of Wing-1 (incremental volume of production) of DRP Framework: yield improvements by enhanced genetic potential (GenPot, Pillar 1), reduction in existing yield loss through improved management (ManPot, Pillar 2) and production increase by exploring unexplored spaces for rice (SpacePot, Pillar 3). Two targets of future rice production were set: (i) reference minimum production to achieve (Ref-MinPro) and (ii) the reference maximum production potential (Ref-MaxPro).

Sensitivity of future rice production was studied under four scenarios: (i) zero success (0%) in the interventions as planned in relation to the three pillars, or in other words, progress will remain halted as it is as of now; (ii) 25%, (iii) 50% and (iv) 75% success in the interventions across the three pillars. The analysis undertook quantifying the impact four sensitivity circumstances on the production targets. The outputs of the four scenarios were compared with the set of annual rice production target (RPTa) and expressed as percent change. In the same way, the sensitivity of the labour productivity was analyzed and compared.

Mechanisms for speeding up adoption-cycle

A new 'Generic rice variety adoption' (GRVA) model was developed by using cumulative Beta distribution function (Salam *et al.*, 2003), and parameterizing with data of variety adoption rate. For this purpose, long-term (1991-2018) data of nine varieties were sourced from the Agricultural Economics Division of BRRI (Rice Database, BRRI website: www.brri.gov.bd).

The accelerated diffusion for newly released rice varieties (AD4NRV) model was newly developed based on a blueprint. The blueprint was constructed through a small group discussion.

An experimental sensitivity was conducted in a four-by-four matrix of two factors (auxiliary variables): amount of base seed available from research institute (500, 600, 700 and 800 kg) and farmers seed retention (20%, 25%, 30% and 35% of produced seeds). Two outputs - number of demos to be need and adoption in percent area – were compared with three reference of points (current adoption peak of 16 years (LAP16), the peak cut by 3 (LAP13), and 6 (LAP10) years.

Approaches of Adding Value to Rice

A profile of nutritional status and potential product diversity of BRRI-released varieties were developed based on nutraceutical properties with reference to BRRI threshold. The nutraceutical properties, including grain quality, were assessed following standard methods referenced in the Table 1.

Identification of Rice Production Challenges, and Measuring Successes in Productivity

An outline of current rice production environment of Bangladesh was composed using perception, idea and information from literature and expert consultation.

Estimation of yield trend of clean rice

The trend in clean rice yield was estimated by fitting the five-year averaged data using an exponential growth model during the period of 1960 to 2015. The national data was sourced from FAOSTAT (http://www.fao.org/faostat/en/#data/QC). The trend line was forwarded to 35 years through to 2050.

Relationship between climate variables and rice yield

The potential evapotranspiration (ET_0) was calculated for Boro rice season using monthly average historical weather data for the period of 1981 to 2016 sourced from the Bangladesh Meteorological Department (BMD). The weather variables, included minimum temperature, maximum temperature, relative humidity, wind speed and bright sunshine hours, used as inputs of the FAO developed Cropwat8.0 model (Allen *et al*., 1998) to obtain ET_0. Sen's slope estimator (Sen, 1968) was applied in the model for estimating long-term changes in the ET_0. To relate the estimated changes in ET_0 to Boro rice, the yield data were obtained from the Bangladesh Bureau of Statistics (BBS, 2018). We used the yield data for four Department of Agricultural Extension (DAE) designated regions - Faridpur, Khulna, Mymensingh, and Rajshahi. We purposely selected the four regions because the estimated ET_0 of the regions had shown marked decline in ET_0 over the years.

The relationship between country-averaged annual temperature and national rice yield for the period 1961 to 2016 was estimated. For this, rice yield data were obtained from Bangladesh Bureau of Statistics (BBS 2018), and the temperature data from the International Rice Research Institute (IRRI) (http://ricestat.irri.org:8080/wrs). The IRRI-sourced temperature data were the anomalies in the weather variable using the base period of 1965 to 1980. In the same line of temperature anomaly, the rice yield anomaly was calculated for the purpose of comparison.

Sustainability

A framework for rice sustainability was conceptualized and developed by following the SDG indicator no. 2.4.1 (http://www.fao.org/3/ca7154en/ca7154en.pdf).

Table 1. List of nutraceutical properties and developed rice-based products together with the reference(s) followed for their estimation, and reference value of their categorization.

Parameter [reference followed for estimation]	Threshold*
Protein [Ma and Zuazaga, (1942)]	High protein: ≥10%
Glycaemic index (GI) [Haffner (1986); Psyrogiannis (2003); Keh (2004)]	GI low: ≤55.0; intermediate: >55.0-69, and high: ≥70
Zinc (Zn), Iron (Fe) and Calcium (Ca) [AOAC (1995)]	Zn: ≥19.0 ppm; Fe: ≥10.0 ppm; Ca: 80.0 ppm
Phosphorus (P) [Yoshida *et al*., (1976)]	P: ≥3.0 g kg^{-1}
Antioxidants - Phenolic compound, total antioxidant capacity, DPPH, Ferric reducing antioxidant power [Oktay *et al*., (2003); Banerjee *et al*., (2005); Turkmen *et al*., (2007); QiuY *et al*., (2010)]	-
Water-soluble vitamin – thiamin [Shozib *et al*., (2018b)]	Thiamin: ≥1.0 mg $100g^{-1}$
Fat-soluble vitamin A for 'Golden rice' [Tang *et al*., (2009)]	VitA: ≥8.64** ppm
Gamma amino butyric acid of pre-germinated rice [Siddiquee *et al*., (2017)]	GABA: ≥12.0 mg $100g^{-1}$
Premium quality rice [Custodio *et al*., (2019)]	Export oriented traits****
Saturated fatty acid of rice bran [Gunawan *et al*., (2006)]	Saturated fatty acid: ≤ 21.0%
Gamma oryzanol in RBO*** [Srisaipet *et al*., (2013)]	Gamma oryzanol: ≥1200 mg $100g^{-1}$
Rice-based bakery products (Rice biscuit, energy dense rice biscuit, cake, bread and noodles) [Shozib *et al*., (2018a); Shozib *et al*., (2018b)]	Energy density in energy dense rice biscuit: ≥5.0) indicating 500 kcal per 100 g serving
Indigenous rice-based products (Popped, puffed and flattened rice)	Change in rice shape due to form utility

*Adopted by the Grain Quality and Nutrition (GQN) Division of the Bangladesh Rice Research Institute (BRRI) for inbreds.

** For GR2E Golden rice (Donald MacKenzie, Personal Communication).

*** RBO denote rice bran oil.

**** Traits are aroma, basmati type grain, length >6.61 mm, length-width ratio >3.5.

Food Security

Food self-sufficiency ratio (SSR) is commonly used as an indicator for measuring national food security (Clapp, 2017). This ratio focuses supply side of food availability. To account for the demand side, Chen and Lu (2018) used food security index (FSI); however, ignored some important component of supply side, such as import, export and previous year's carryover. We modified the equation of Chen and Lu (2018) by accounting for those ignored components.

Food security is equivalent to rice security in Bangladesh. In this study, rice security is expressed as rice self-sufficiency ratio (RSSR) in percentage and estimated using the following equation:

$$RSSR_t = \left(\frac{P_t + I_t - X_t + COP_t}{HC_t + NHC_t}\right) \times 100 \text{ ….. Eq. 16}$$

Where, 'P_t' is the domestic production; 'I_t' is the import, 'X_t' is the export; 'COP_t' is the previous year's carryover, 'HC_t' is the human consumption, and 'NHC_t' is the non-human consumption of rice in t^{th} year. A similar unit to be used for all parameter of the Eq. 16. The value of RSSR in a particular year is (i) equal to 100, indicates self-sufficient; (ii) less than 100, indicates deficit; and (iii) greater than 100, indicates a surplus. The annual national rice production data was accessed from various issues of BBS, whereas import and export data from 'IndexMundi' (https://www.indexmundi.com/agriculture/?country=bd&commodity=milledrice&graph, accessed on 17 October 2020). Section 'Demand domain of production flow' presented the procedure of data generation for human consumption and non-human consumption. The COP_t was calculated as:

$$COP_t = (P_{t-1} + I_{t-1}) - (X_{t-1} + HC_{t-1} + NHC_{t-1}) \text{ ….. Eq. 17}$$

where 't-1' is the lag period of t^{th} year.

Concept Development for Rice Price Stability

A policy concept for market price stability was developed based on (i) literature review, and (ii) suggestions of key informants of stakeholders including farmers, traders, researchers and extension personnel.

RESULTS AND DISCUSSION

Rice Productivity, Production and Sensitivity

The concept of doubling rice productivity (DRP) framework

Figure 2 depicts the concept of doubling rice productivity (DRP) framework, consists of three wings – increase in the volume of production (Wing-1), decrease in per unit area of labour use in the production systems (Wing-2), and adding value to production (Wing-3). Yield enhancement and rice area expansion are the two avenues designated for achieving the goal of Wing-1. For Wing-2, increasing adoption of mechanization has been pointed out which would ultimately impact on labour productivity. Another wing is included in the framework in relation to uplifting the value of production which would potentially contribute to the production increase (Wing-3). Improvements in the nutritional quality of rice, and ensuring access to a stable market are the two areas identified as action pathways for Wing-3.

Potential interventions under Wing-1 include enhancement of genetic potential (GenPot, Pillar 1) of rice varieties, minimization of yield loss (ManPot, Pillar 2) and exploration of unexplored spaces (SpacePot, Pillar 3) for rice cultivation. Advancement in conventional breeding, emphasizing hybridization and application of biotechnology are the suggested tools for enhancing and sustaining GenPot. The yield loss due to improper management remains a barrier to enhanced productivity in rice sector in Bangladesh (Ran *et al*., 2018). The improvements in genetic potentials cannot automatically ensure increased productivity unless those are utilized in farmers' fields. Evidence showed, even for extremely successful varieties, also known as mega-varieties[3],

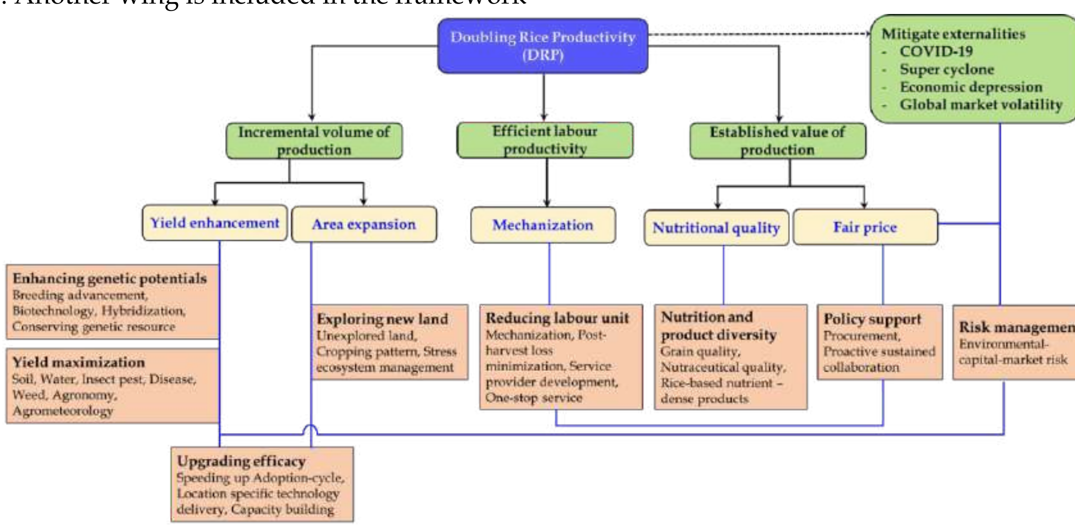


Fig. 2. The proposed concept of doubling rice productivity (DRP) framework of Bangladesh towards meeting the SDG 2.3.1 and moving forward.

[3] A variety is designated as a 'mega-variety' which, within its adoption cycle, receives significant area coverage (perceived as at least 25%) in a growing season.

the adoption lag had been very high. For example, BR11 took 13 years, BRRI dhan28 took 19 years and BRRI dhan29 took 13 years to reach their adoption peak (Kabir *et al.*, 2015). This framework has emphasized on finding interventions on speeding up the adoption-cycle for promising rice varieties.

The DRP framework highlights annualized yield loss scenarios for each management component of rice – agronomy, soil, water, biotic and abiotic agents, harvesting and post-harvesting, and unpredicted weather-related stresses. Besides, the arable land in the country has been shrinking (@ 0.4% annually, The Daily Prothom Alo, 2015) over time that also aggravated the rice security challenges (Hasan *et al.*, 2013; Alam *et al.*, 2015). However, there is a considerable volume of culturable waste land that has the potential to contribute to the national rice basket subject to undertaking situation-specific interventions.

Doubling productivity, concerning rice is a target for meeting SDG 2.3.1. Rice is a staple food in the country that has immense significance in the economy and politics that pointed out the gravity of the goal. Farm mechanization is a key to transforming subsistence agriculture into commercial agriculture in Bangladesh (Van Loon *et al.*, 2020). The framework (Fig. 2) has categorically directed to explore the action-points of how the on-going momentum of mechanization can be translated into reality in meeting the SDG.

The framework (Fig. 2) has also figured out that for sustaining rice productivity and production in Bangladesh, it would need to add value to rice commodities (Singh *et al.*, 2002), such as nutritional improvements, product diversity, and safety. It has further added market risk management and rice procurement policy support to ensure that rice becomes a profitable crop to farmers. All the wings and underlying intervention will contribute to increased rice productivity and production to remain Bangladesh as a rice surplus country and become an influential actor in the rice world.

Another component, the externalities (termed as 'perturbation' by Conway, 1987), can suddenly and strongly disrupt the existing rice production system, such as COVID-19, that would affect sustainability. The proposed framework has specified the pathway to mitigate those externalities.

Improving genetic potential

The GenPot has been set in such a way that the minimum requirement of rice production (Ref-MinPro) for the country could entirely be met through to 2050 by this pillar alone, one of the major incremental rice production and productivity pillars. According to the estimation, to achieve the Ref-MinPro for the year 2030, the GenPot has set as 4.79 t ha^{-1} as clean rice (7.15 t ha^{-1} as rough rice) from 3.94 t ha^{-1} as of 2015 productivity. For 2050, this GenPot is set as 6.06 t ha^{-1} (9.05 t ha^{-1} as rough rice) (Fig. 3). The improvements in GenPot will be made possible by using modern biotechnological methods and tools such marker assisted selection (MAS), genome editing, speed breeding, etc (details in Rabbi *et al.*, 2020). This estimation has been made with the assumption that the current yield loss status (20.61%) will remain unchanged during the study period, as if the variety will perform in full potential without encountering any yield loss.

Minimizing yield loss

Determinants and partitioning of yield loss

The rice cultivars are unable to perform to their full potential due to yield loss (YL) because of stress and/or improper management at any of the 17 stages of the rice crop life-cycle. The yield detrimental factors included agronomic, soil and water mismanagement issues, biotic and

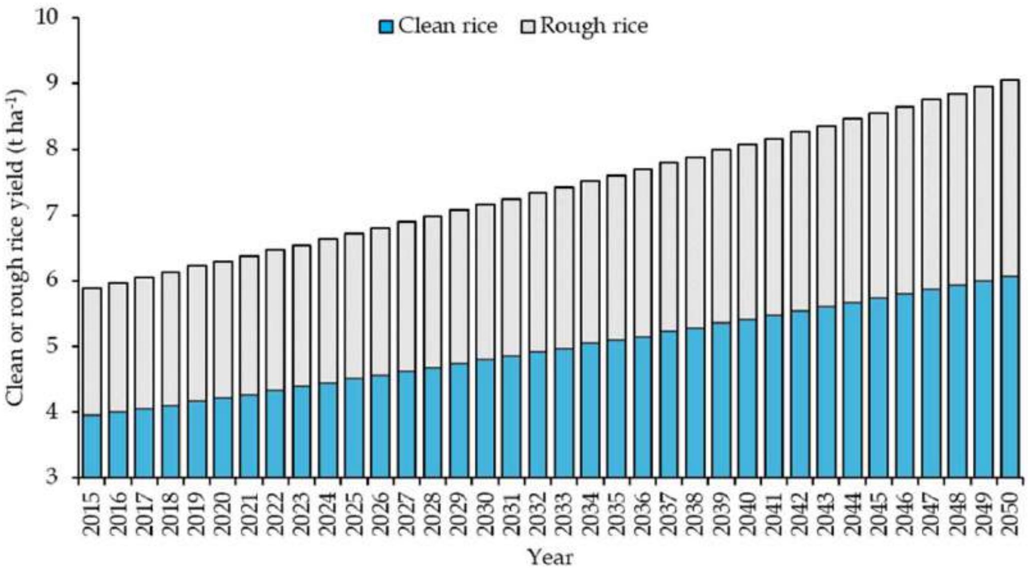


Fig. 3. Estimated genetic potential of clean and rough rice in Bangladesh with the assumption that current yield loss status will remain unchanged during 2015-2050.

abiotic threats, harvesting and post-harvesting mishandling and unanticipated climate hazards. These factors were accounted for as determinants of YL. Conventionally, YL is estimated comparing treatment (i.e., full interventions) with control (i.e., without interventions) for individual YL-determinants. For example, indirect wet seeded rice about 82% YL has been reported if not weeded (Bhuiyan, 2016). The YL due to improper weeding in the farmer's field in Bangladesh has been found in the range of 4.25% to 20.00% depending on different rice ecosystems (Bhuiyan *et al*., 2018). The YL from rice hispa was reported as high as 32.85% (Bari *et al*., 2012). Shahjahan *et al*. (1994) recorded an YL of 31% when the crop was infested with sheath rot disease at the critical stage. While those losses, may be called management potential (ManPot) losses, can occur in specific on-field circumstances and specific seasons; they do not represent the scenario of all the fields of a country in all the seasons in all the years. To represent the reality, we have estimated the 'annualized YL' which can be treated as recurring year after year.

The total loss from all YL-determinants has been estimated as 20.61%. This figure is very similar to that reported by Kabir *et al*. (2015). In this study, we have partitioned this loss into 14 YL-determinants through expert elicitation workshops (Fig. 4). For example, agronomic management related analyzed YL has been estimated as 11.35% arising from seed quality and tillage (SQ&T, 1.00%), time of sowing/transplanting (Planting, 4.75%), seedling age (SIA, 2.50%), spacing (Spa, 1.20%) and weed management (WdM, 1.90%); soil and moisture stress-related losses as 4.50% for fertilizer management (FM, 4.00%) and water management (WM, 0.50%); abiotic and biotic stresses as 2.50% for diseases (D, 1.00%), insect-pest (P, 1.00%) and all abiotic stresses (A, 0.50%); and post-maturity as 2.01% from harvesting (H, 1.00%), post-harvesting (PH, 1.00%) and processing (0.01%). Besides, annualized YL from natural calamities (NC) is estimated as 0.25%.

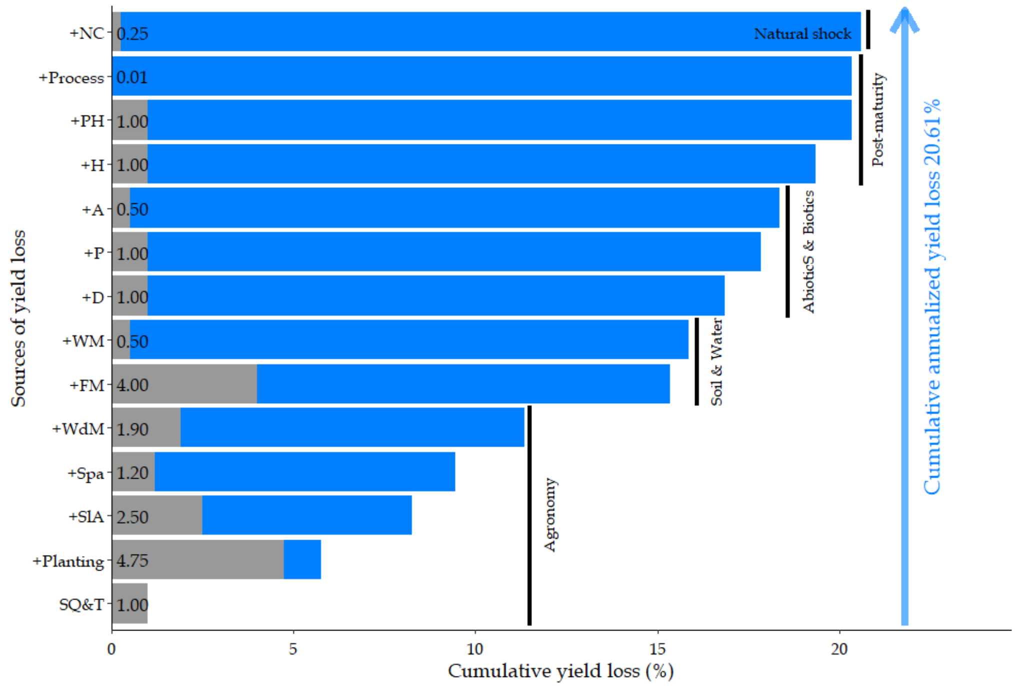


Fig. 4. Cumulative annualized rice yield loss in Bangladesh accounting for 14 yield-loss-determinants at different phases of production systems. 'SQ&T' denotes for seed quality and tillage, 'Planting' indicates time of sowing / transplanting, 'SIA' for seedling age, 'Spa' for spacing, 'WdM' for weed management, 'FM' for fertilizer management, 'WM' for water management, 'D' for diseases, 'P' for insect-pest, 'A' for all abiotic stresses, 'H' for harvesting operations, 'PH' for post-harvest management, 'Process' for all sort of processing, and 'NC' for natural calamities.

Measures to reduce the yield loss

Figure 5 presents that the yield loss will be decreased to 13.05% in 2030 and 7.10% in 2050 from the baseline (2015) figure of 20.61%, through implementation of means and methods suggested in recent and contemporary research papers (Islam, 2020; Bhuiyan *et al.*, 2020a; Bhuiyan *et al.*, 2020b; Rabbi *et al.*, 2020; Rahman *et al.*, 2020; Shozib *et al.*, 2020; Ali *et al.*, 2020; Khatun *et al.*, 2020; Hossain *et al.*, 2020, Kabir *et al.*, 2020).

Plan and activities have been formulated in order to minimize yield loss in ManPot accounting for each of the 14 designated yield loss determinants (Fig. 6). For example, production gain of 0.79 and 1.97 MT by 2030 and 2050, respectively, will be achieved through managing the time of sowing/transplanting. Proper fertilizer management will ensure 0.68 MT production gain by 2030 and 1.66 MT by 2050. Similarly, 0.22 and 0.41 MT gain in production will occur in 2030 and 2050, respectively, through managing diseases; a similar gain has been estimated from managing insect-pest (Fig. 6).

A number of cutting-edge technologies will be adopted to address to improve ManPot. For example, the rice yield loss from insect-pest will be reduced following recommendations based on early warning systems (Salam *et al.*, 2019b), smart pest management systems, and implementing precision insecticide application technologies (Ali *et al.*, 2020).

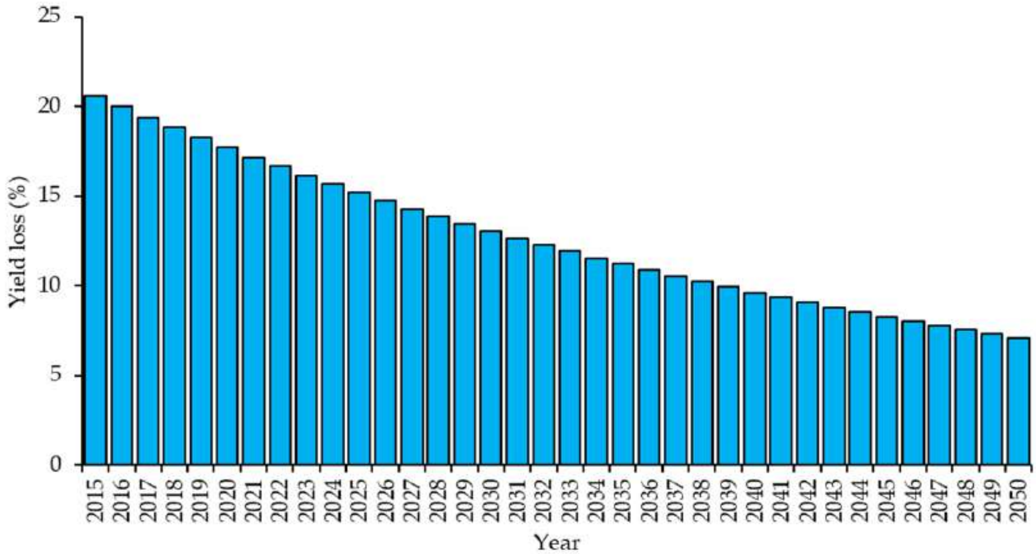


Fig. 5. Planned reduction of yield loss in Bangladesh in annual step during the period of 2015-2050.

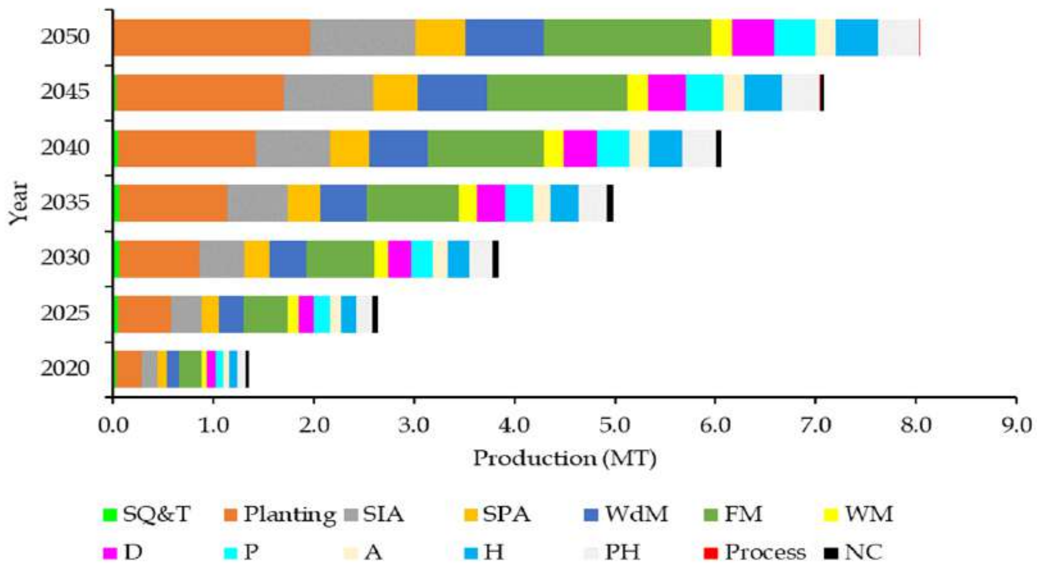


Fig. 6. Estimated clean rice production gain in Bangladesh under 14 yield-loss-determinants (ManPot) at different phases of production systems. 'SQ&T' denotes for seed quality and tillage, 'planting' indicates time of sowing /transplanting, 'SIA' for seedling age, 'Spa' for spacing, 'WdM' for weed management, 'FM' for fertilizer management, 'WM' for water management, 'D' for diseases, 'P' for insect-pest, 'A' for all abiotic stresses, 'H' for harvesting operations, 'PH' for post-harvest management, 'Process' for all sort of processing, and 'NC' for natural calamities.

Moreover, the disease-related yield loss of 1.0% in 2015 will be reduced to 0.7% by 2030 through adopting digital tools for data collection, early warning system for supporting decision-making, provision of agro-advisory, effective training for farmers and extension agents at grassroots level, regular field monitoring, and reviving indigenous technologies (such as adjusting crop density, depth of planting, adjusting time of planting, altering of plant and crop architecture, and mulching) (Khatun *et al.*, 2020). Furthermore, yield loss during post-maturity can be minimized through scale-appropriate mechanization such as using reaper, combined harvester, mechanical thresher, and mechanical dryer (Islam, 2020).

Change management easing pressure on target genetic potential

We compared required genetic potential (GenPot) under two scenarios, where both achieve the minimum production requirements (Ref-MinPro) of rice: a constant yield loss of 20.61% as of current management, and incrementally decreasing yield loss coming down to 7.10% in the year 2050 through improved management. An exponential model was used to fit the data.

We report that the estimated GenPot of 4.8 t ha^{-1} as clean rice (7.1 t ha^{-1} as rough rice) and 6.1 t ha^{-1} (9.1 t ha^{-1} as rough rice) for 2030 and 2050, respectively, to achieve the Ref-MinPro (Fig. 7). Realizing an annualized clean rice yield of 6.1 t ha^{-1} (9.1 t ha^{-1} as rough rice) in 30 years from now, which will need a continued improvement in GenPot @1.23% $year^{-1}$ (equivalent to 61 kg ha^{-1}), could be a mammoth task for the breeders. This pressure would be eased by incrementally decreasing yield loss through to 2050 from 20.61 to 7.10% (Fig. 5) by adopting improved management. This will result in the requirement of lower GenPot, 4.4 t ha^{-1} as clean rice (6.6 t ha^{-1} as rough rice) and 5.2 t ha^{-1} (7.7 t

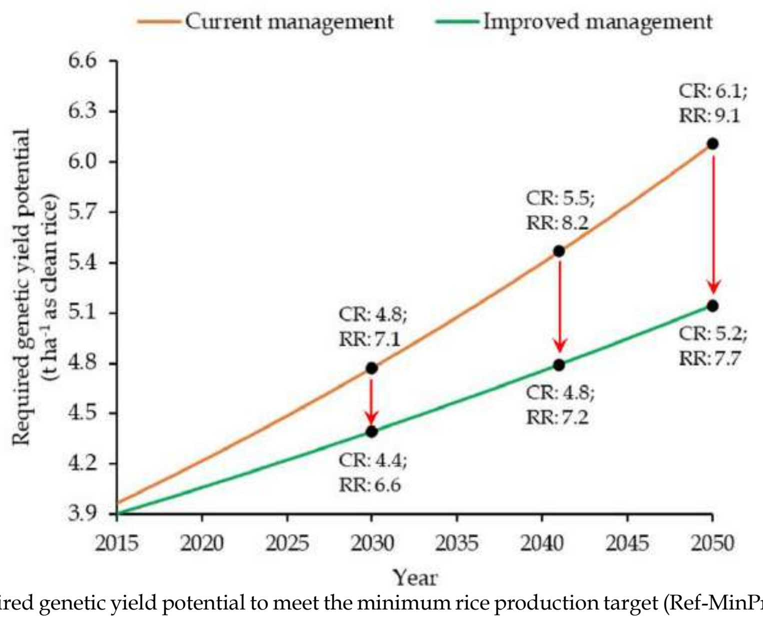


Fig. 7. Required genetic yield potential to meet the minimum rice production target (Ref-MinPro) across 2015 to 2050. Two scenarios are shown: the yield loss will remain unchanged (Current management) and reduction in yield loss @3% $year^{-1}$ (Improved management). Red colour arrows indicate the ease of pressure. Filled circles on the lines indicate corresponding yields for 2030, 2041, and 2050. 'CR' and 'RR' denote for clean and rough rice yield, respectively.

ha^{-1} as rough rice) for 2030 and 2050, respectively, by maintaining genetic improvement @0.79% year^{-1} (equivalent to 36 kg ha^{-1}).

The rate of yearly change of GenPot for current and improved management was calculated. The relative contribution of improved management was estimated as the ratio of the difference in the rate of yearly change between the management to the rate of change under current management. The relative contribution was expressed as percentage. Results show that improved management will reduce the required rate of genetic gain by ~41% while hitting the target of the Ref-MinPro. In other words, the average co-contribution of improved management will gain ~41% to rice productivity compared to current management.

It is generally agreed that both breeding and agronomy (i.e. management) have contributed to yield advances although the relative contributions of each have varied according to the crop species and environment (Anderson *et al*., 2005). Table 2 shows that the desired rice productivity under long-term changing yield loss (YL) scenarios will be achieved in combination of four contributors – genotype (G), management (M), environment (E) and people (P). To estimate historical YL, we developed a model to back calculate the loss based on 2015 – 2050 estimations; on the other hand, partitioning of yield contributors was undertaken from literature (Salam *et al*., 2016). With the aimed gradual decrease in YL, the contribution of 'G' and 'M' will increase, respectively, from 8.00% and 40.00% in 1971-75 to 23.67% and 48.19% in 2046-50 (Table 2). During the periods, environmental influence (E) on yield will reduce because of improvements in genotype and management. The technology development will enhance people's (P) efficiency; thus, the relative contribution of this yield-contributor will automatically reduce. It has been reported that about 70% of yield improvement achieved from improved management and about 30% from improved cultivars of wheat in Western Australia (Anderson *et al*., 2005), whereas Abrecht *et al*. (2008) observed 40%, 16% and 16% wheat yield variation though management, genotype and environment, respectively. For rice, according to farm survey 2017, genotype contributed to yield variation by 24%, management by 46%, and environment and people combinedly by 30% (Naris Parvin, unpublished PhD research). Findings show that emphasizing on improved management can considerably ease the increasing pressure on achieving genetic potential for future rice varietal development.

Exploring the unexplored spaces for increased production

There still remain some areas which can be brought under rice cultivation by creating irrigation facilities. This study has identified five such potential spaces across the country. The potential area coverage, including productivity and production, in those spaces are presented below.

Area and productivity of rice in five unexplored spaces

About 0.26 M ha of land with a target clean rice yield of 3.69 t ha^{-1} has been estimated to bring under Boro rice cultivation by 2030 in Space 1; this estimated area to be raised to 0.50 M ha (with the target clean rice yield 4.49 t ha^{-1}) in 2050 (Fig. 8). This would be possible by facilitating irrigation and sourcing water from re-excavation of canals in the greater Barishal region. Strong community motivation would be required to harvest success from this initiative.

In Space 2, the estimated area has been set to about 0.13 M ha (targeting clean rice yield 3.63 t ha^{-1}) in 2030 under Aus and Boro rice in the fallow lands in north-eastern Bangladesh specifically in greater Sylhet region. This can be executed by developing irrigation facilities.

Table 2. Estimated yield loss, and relative rice yield contribution of genotype, management, environment and people in Bangladesh. Figures represent five-year annualized values that incorporate all the three rice growing seasons and all the environments across the country.

Period (Year)	Yield loss (%)	Relative yield contribution* (%) of			
		Improved genotype	Responsive management	Favourable environment	Peoples' direct engagement
1971-1975	35.48	8.00	40.00	22.00	30.00
1976-1980	33.78	8.60	40.50	21.73	29.18
1981-1985	31.88	9.25	41.01	21.45	28.30
1986-1990	29.98	9.94	41.52	21.19	27.36
1991-1995	28.08	10.68	42.04	20.92	26.36
1996-2000	26.18	11.49	42.56	20.66	25.29
2001-2005	24.29	12.35	43.10	20.40	24.16
2006-2010	22.39	13.27	43.63	20.15	22.95
2011-2015	20.67	14.27	44.18	19.89	21.66
2016-2020	18.83	15.34	44.73	19.65	20.29
2021-2025	16.17	16.49	45.29	19.40	18.82
2026-2030	13.88	17.72	45.86	19.16	17.26
2031-2035	11.92	19.05	46.43	18.92	15.60
2036-2040	10.24	20.48	47.01	18.68	13.82
2041-2045	8.79	22.02	47.60	18.45	11.93
2046-2050	7.55	23.67	48.19	18.22	9.92

* Annualized figure, estimated by the authors' using modelling technique; assumptions validated through published national data.

The area is estimated to cover 0.30 M ha (with targeting clean rice yield 4.39 t ha^{-1}) in 2050 (Fig. 8). About 0.13 M ha (target clean rice yield 3.73 t ha^{-1}) and 0.31 M ha (target clean rice yield 4.50 t ha^{-1}) of a section of saline belt of Southwest and greater Jashore region has potential to be under Boro rice cultivation by 2030 and 2050, respectively, through facilitating surface water irrigation (Space 3).

Coastal char land in greater Barishal region and Noakhali district (Space 4) has been estimated to accommodate high yield potential T. Aman rice in about 0.09 and 0.20 M ha of land by 2030 and 2050, respectively.

We have explored the Chattogram hill tracts, especially Kaptai lake areas (Space 5), having potential to grow Boro rice, but constrained by lack of irrigation facilities. In this Space about 0.04 M ha of fallow land has been estimated to bring under rice by 2030, and 0.07 M ha in 2050 through facilitating irrigation management (Fig. 8). In addition, adaptive research to test varieties and extension programmes are also important to expand rice cultivation in fallow areas.

Rice production from unexplored spaces

Considering the estimated target area and yield (Section 'Area and productivity of rice in five unexplored spaces'), in the five unexplored spaces, the combined annual production (SpacePot[4]) is estimated from 2020 through to 2050 (Fig. 9). By complementing initiative, the country will potentially be able to produce 0.83 MT clean rice in 2030 and 1.06 MT in 2050.

[4] Added rice production in potential unexplored spaces (Section 'Estimation of production in the unexplored spaces')

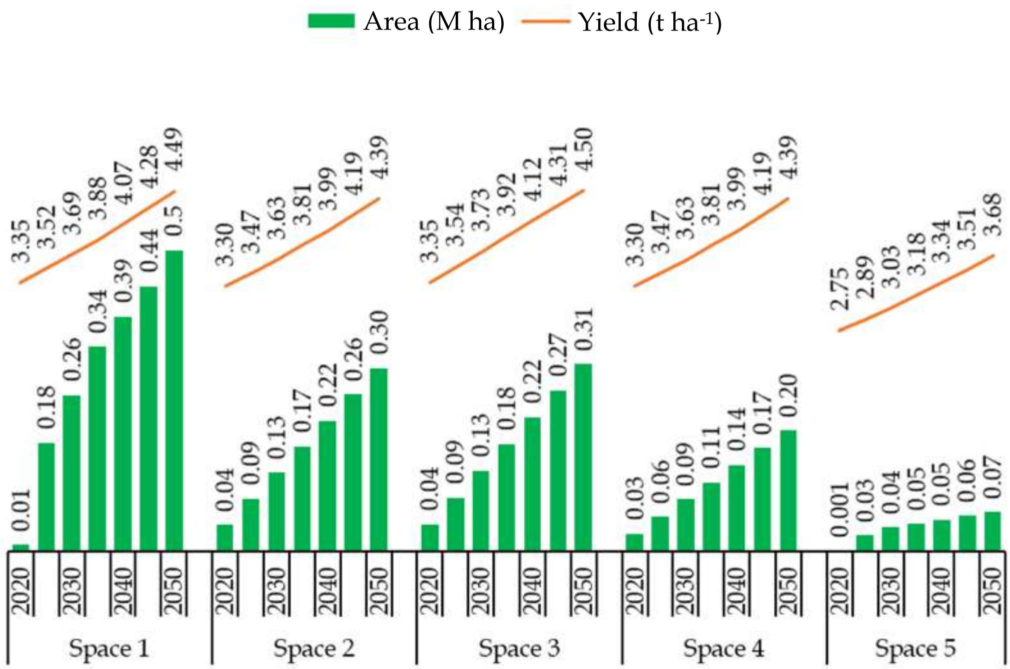


Fig. 8. Estimated area and yield of rice in five unexplored spaces of Bangladesh presented in a five-year step during 2020-2050.

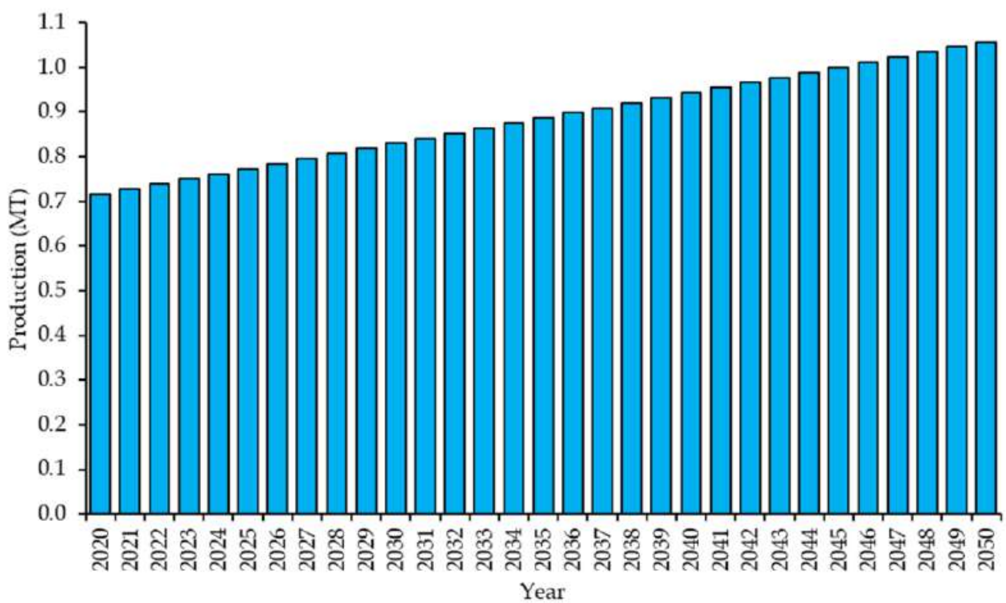


Fig. 9. Accumulated clean rice production from five unexplored spaces in Bangladesh during 2020 – 2050.

Production flow: Hitting the production targets

The flow of the future rice production in Bangladesh will stem from three pillars - GenPot (vertical dimension), SpacePot (horizontal dimension) and ManPot (cross-dimension). The future potential rice production estimates, from individual or combinations of the three pillars, have been compared with two reference targets: (i) the minimum production target or 'Ref-MinPro' across 2050 (35.29, 40.40, 43.80 and 47.20 MT in 2015, 2030, 2040 and 2050, respectively; red line in Figure 10, Kabir *et al*., 2015), and the maximum production potential or 'Ref-MaxPro' across 2050 set in this paper (blue line in Fig. 10). As shown in Figure 10, achievement in vertical dimension alone (i.e., GenPot) will meet the Ref-MinPro in 2050 (47.20 MT). The Ref-MaxPro will results from the combined achievements in three pillars, with which the country will be surplus of about 13.65 MT of rice by 2050. This surplus production will act as a 'pool' to overcome crop damage resulting from any externalities in production systems. A part of any such surplus will be available for (i) longer-term storing, (ii) exporting, and (iii) producing diverse rice-based products.

Estimation of rice utilization flow

Figure 11 presents annual demand for clean rice in Bangladesh for human consumption and non-human utilization from 1972 to 2050. The demand in 2020 has been 2.3 times higher compared to 1972, 2.0 times for human and 3.4 times for non-human purposes. The demand for clean rice in 2030, 2040, and 2050 has been estimated as 36.03 MT (human consumption: 26.17 MT; non-human utilization: 9.86 MT), 37.96 MT (human consumption: 27.06 MT; non-human utilization: 10.91 MT), and 40.70 MT (human consumption: 28.70 MT; non-human utilization: 12.00 MT), respectively (Fig. 11).

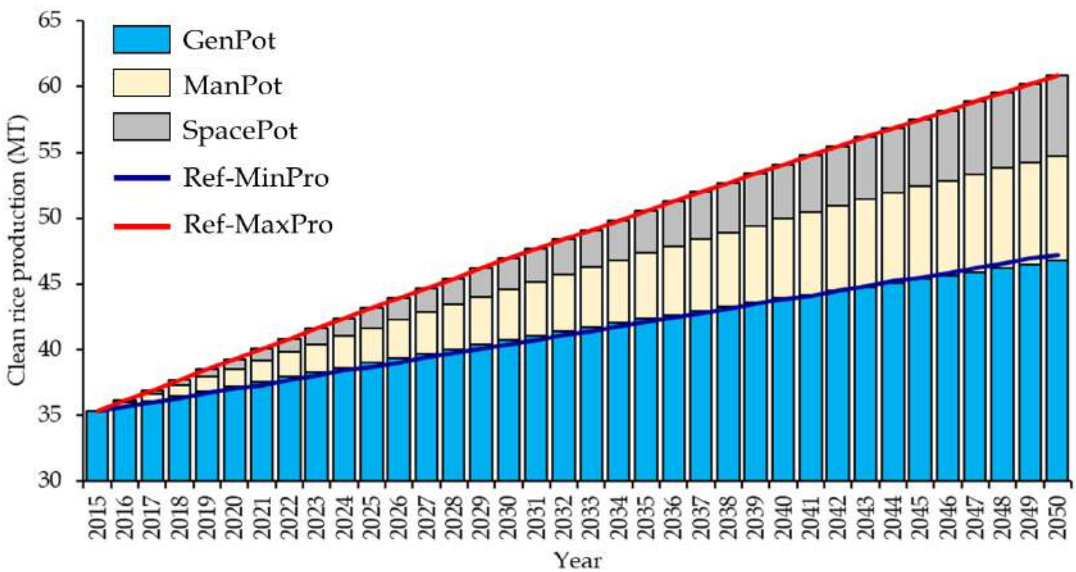


Fig. 10. Recent trend (2015-2019) and estimated future (2020-2050) rice production in Bangladesh through the three pillars of production increases – genetic potential (GenPot), management potential (ManPot) and spaces potential (SpacePot) during the period of 2020-2050. Also shown the reference minimum production (Ref-MinPro) target to achieve (solid red line) and reference maximum production (Ref-MaxPro) target (solid blue line) during the same period.

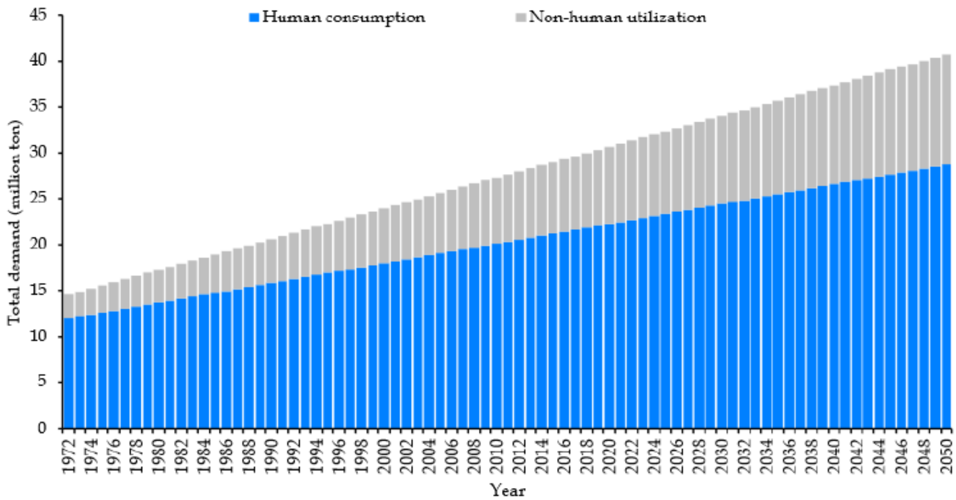


Fig. 11. Historical (1972-2020) and estimated future (2021-2050) demand of clean rice in Bangladesh under two purposes, human consumption and non-human utilization.

Labour productivity

The rice labour productivity in Bangladesh will double in 2029 considering a base productivity index of '1' in 2015 (Fig. 12a). This achievement will duly meet the SDG target 'doubling productivity' of 2030. Production will be one of the three drivers of labour productivity (Fig. 1). Based on continued success in genotype improvements under favourable and constraint environments, and adoption of modern varieties and improved management, it is unlikely that rice production of the country will negatively impact on labour productivity. The other two drivers, rice price and farm power availability, will be the determinants of future labour productivity (Fig. 1). We have estimated the required rice price and farm power for 2029 to meet the doubling labour productivity; for the year, the price, as clean rice, has set as BDT 48.40 kg^{-1} (equivalent rough rice price of BDT 32.43 kg^{-1}), while the farm power availability as 2.71 kW ha^{-1} (Fig. 12b). The required clean rice price can be ensured by a @3.00% incremental increase in the base year (2015) price BDT 32.00 kg^{-1} (equivalent rough rice price of BDT 21.44 kg^{-1}). On the other hand, the required farm power can meet by enhancing its availability @3.76% annually. This can be achieved by public-private investment on research, development and extension, developing scale-appropriate machineries, entrepreneurship development, capacity development of service providers, and enhancing synchronized cultivation (details in Islam, 2020). Historically, the speed of mechanization, with respective to farm power availability, in Bangladesh is not far behind of India (Singh *et al*., 2014). The 2013 data shows the available farm power was 10.60, 5.70, 2.50, 2.02, 1.70, 1.32, 1.10 and 0.20 kW ha^{-1} in the Republic of Korea, China, Thailand, India, Vietnam, Cambodia, Pakistan, and Malaysia, respectively. The corresponding figure (1.83 kW ha^{-1}) for Bangladesh indicates the country is ahead of many comparable Asian countries (Khan and Rehman, 2019). It is expected that, the research, extension, and market will continue their endeavour for increasing the labour productivity to meet up the demand of 215 million people in 2050 (Kabir *et al.*, 2015).

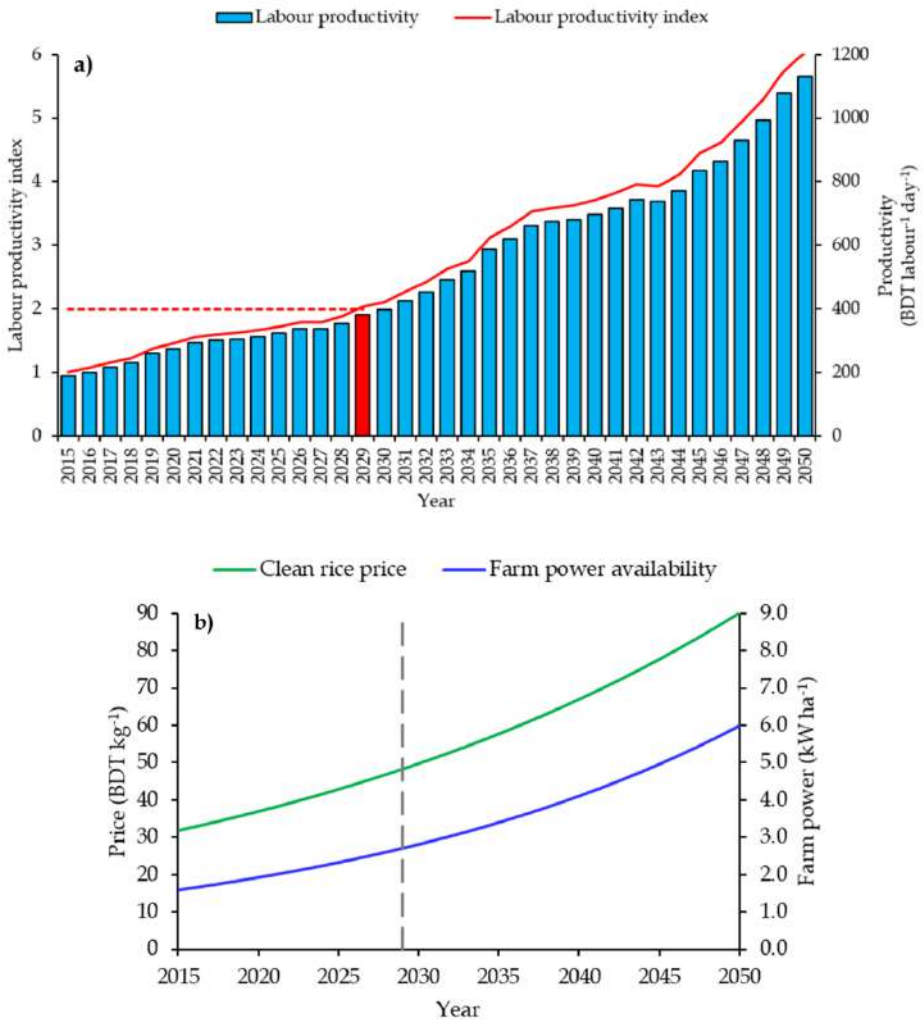


Fig. 12. Recent trend (2015-2019) and estimated future (2020-2050) rice labour productivity (BDT labour^{-1} day^{-1}) and productivity index (a), and clean rice price (BDT kg^{-1}) and farm power availability (kW ha^{-1}) (b) in Bangladesh. The red bar (a) and vertical broken line (b) indicate the time of achieving doubling rice labour productivity mark.

Sensitivity to production flow and labour productivity

Sensitivity analysis shows that under zero progress in estimated production flow in the three pillars – GenPot, SpacePot and ManPot – the country will face 18.99 and 36.00% shortfall of Ref-MinPro in 2030 and 2050, respectively (Fig. 13). This shortfall will reduce to 10.23 and 19.61% in 2030 and 2050, respectively, if 25% progress is achieved in the three pillars, and even 50% progress will still result in small deficit. Analysis further reveals that 75% progress in the achievement will provide 7.33 and 12.91% gain above the Ref-MinPro (Fig. 13).

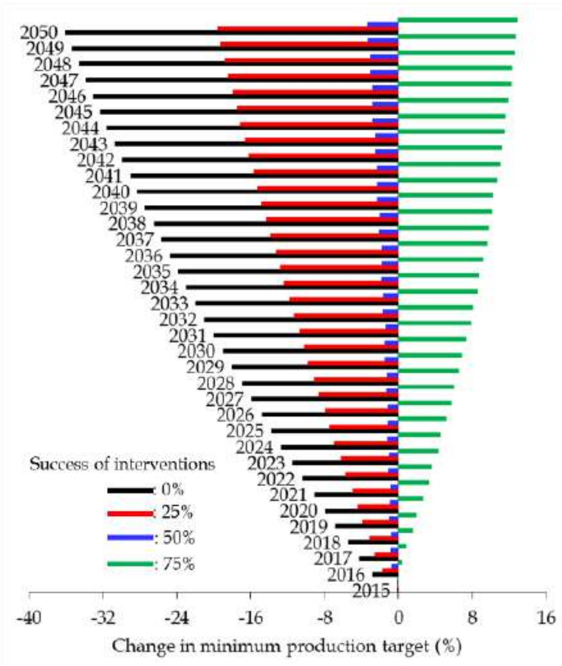


Fig. 13. Sensitivity in future rice production of Bangladesh under four scenarios of the three pillars of production increase – genetic potential (GenPot), management potential (ManPot) and spaces potential (SpacePot) during the period of 2015-2050.

On labour productivity, zero progress in the estimated production flow will result in 17.28 and 30.15% shortfall in set-target (Ref-MinPro) in 2030 and 2050, respectively (Fig. 14); this shortfall will narrow down to 9.36 and 16.49% in 2030 and 2050, respectively, if 25% progress is achieved across the three pillars. The analysis indicates 50% progress in the estimated production flow will still result in small shortfall in labour productivity, which, however, will turn into 6.51 and 10.61% gain above the set-target (Ref-MinPro) through 75% progress in the achievement.

The results suggest that continued interventions in the three pillars of production flow would need to be planned and executed through research and extension to materialize at least 75% of the estimated production flow which will lead the country to a satisfactory production level to 'feed the future' through sustaining rice-food security.

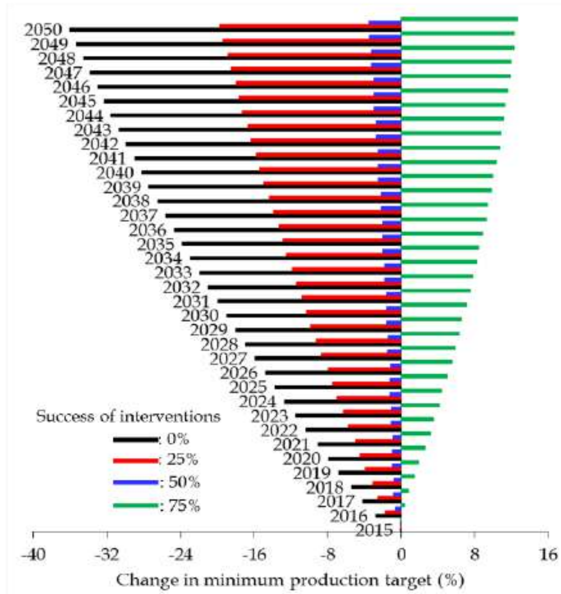


Fig. 14. Sensitivity in future rice labour productivity of Bangladesh under four scenarios of the three pillars of production increase – genetic potential (GenPot), management potential (ManPot) and spaces potential (SpacePot) during the period of 2015-2050.

Speeding up Adoption-cycle of Promising Rice Varieties

Generic rice variety adoption model

Delay in adoption of promising rice varieties in Bangladesh is a barrier to harvest the full potential of those varieties before deteriorate their genetic potential and/or rapid national production gain. It takes, on average, 16±3 years to reach adoption peak of the most successfully adopted rice varieties, or in other words 'mega-varieties', in Bangladesh (Kabir *et al*., 2015). A generic rice variety adoption (GRVA) model was developed to study the behaviour of the adoption curve with the change in the time requires to reach adoption peak (LAP). The model estimated the generic LAP of 16 years (LAP16) based on adoption pattern of nine rice varieties (Fig. 15). The model further identified a lag period of three years after which a variety adoption kicks-off exponentially; we term this period as 'diffusion period' (DP) of rice variety adoption. In experimentation with the GRVA model, we curtailed this LAP16 by 3 (LAP13) and 6 (LAP10) years and noted that the earliness in LAP is achieved by 'the area coverage of the concerned variety at the end of DP'; we term it as diffusion intensity (DI) having a unit of percentage. Thus, DI is the major driver for the LAP. In other words, to achieve a target LAP, one needs to ensure the right DI.

Accelerated diffusion for newly released rice varieties

In order to ensure the right DI for curtailing LAP, we investigated into ways and means and synthesize those into an accelerated diffusion for the newly released rice varieties (AD4NRV) model. The blueprint of AD4NRV model is presented in Figure 16.

According to the model, the concerned institute will produce seed during the variety-releasing year. We term the seed as 'Base seed'. The volume of the base seed will depend on the target area to be set according to breeders' confidence and institutional strength, agro-ecological suitability, farmers' and consumers' preference, and any such related factors. The model will generate information in a yearly time-step over a period of three-years. This three-years

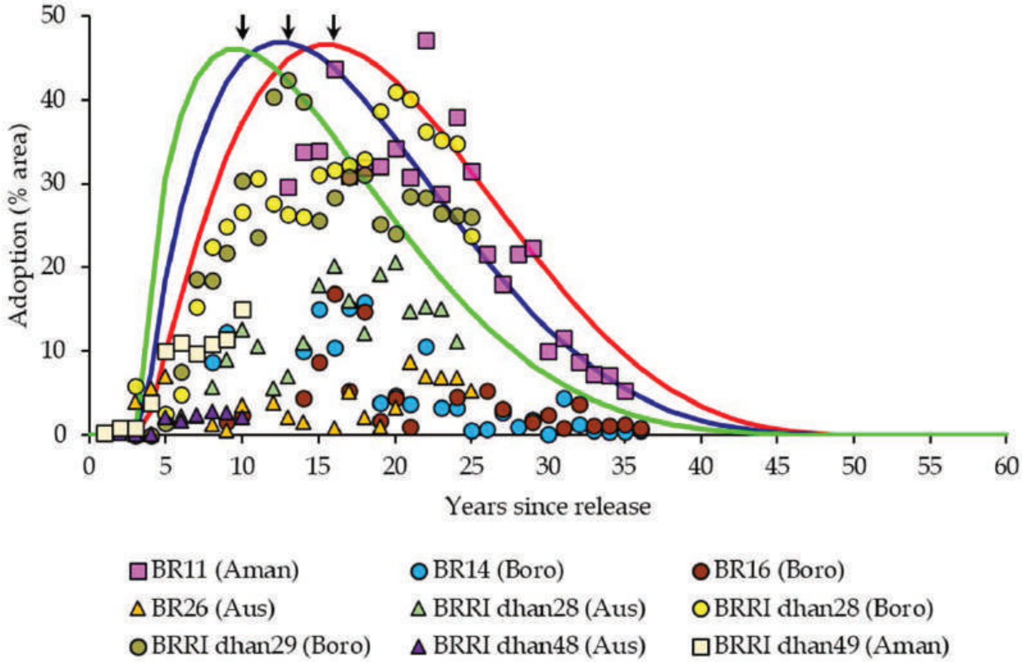


Fig. 15. Generic rice variety adoption (GRVA) model of Bangladesh (Red line). Blue and green lines indicate the shift in the length of adoption peak (LAP) that from the model by three and six years. Arrows denote for adoption peaks. The symbols show measured adoption (% by area) of nine rice varieties since released. In legend, parentheses used with varieties indicate the growing seasons; 'Aman' represents the T. Aman season.

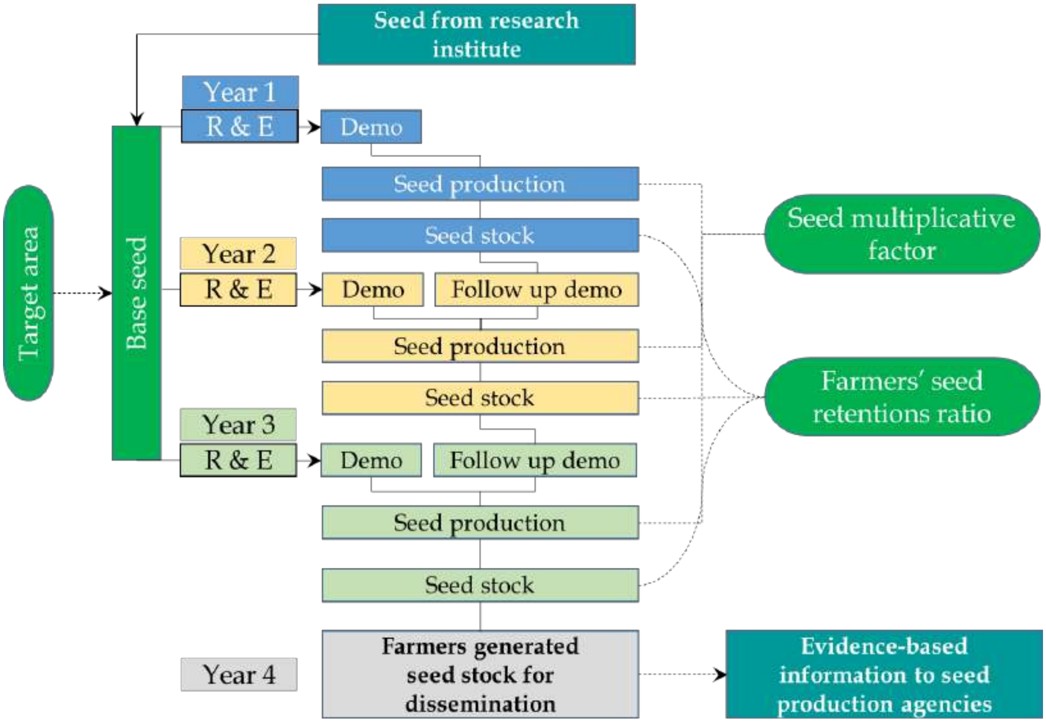


Fig. 16. Blueprint of accelerated diffusion for newly released rice varieties (AD4NRV) model. Rectangles are state variables or time period or execution bodies, while the ovals are auxiliary variables. Solid arrows and lines show material flow, and broken arrows and lines indicate information flow in the model. Blue, gold and light green rectangles represent the first, second, and third year's seed diffusion cycle. The 'R & E' denotes for research and extension.

correspond to DP as observed in AD4NRV model. The seed diffusion will be carried out through two channels – demonstration (termed as 'demo') and follow up demo. The demos will be directly conducted by research and/or extension institutes (R & E), while the follow up demos will be independently carried out by the farmers with required assistance and supervision from R & E. All the seed diffusion activities will be carried out in farmers' fields. The demos, using the base seed, will be conducted in three years, while the follow up demos, using farmers' retained seed, will be carried out in year 2 and 3. Each farmer will use 5 kg seed 'bigha'$^{-1}$ (1 'bigha' = 33 decimal) in demo and/or follow up demos. The model assumes seed multiplicative rate of 80% sown seed, and farmers will retain 20% of produced seed. In the end of three years, the system will generate the diffusion intensity (DI) of the concerned variety. In addition, the output of the AD4NRV model will provide evidence-based information to public and private entities for commercial seed production.

Application of AD4NRV model to determine DI under three LAPs

The AD4NRV model was applied to estimate 16 diffusion outcomes aiming three scenarios of the time required to reach adoption peak – LAP16, LAP13, and LAP10. We used four-levels of two determinants (auxiliary variables):

amount of base seed available from research institute (500, 600, 700 and 800 kg) and farmers seed retention (20, 25, 30 and 35% of produced seeds). BRRI dhan29, a mega-variety, was used a test variety for this analysis which received a maximum adoption of 42% by area during Boro season.

Results reveal that to achieve the diffusion intensity (DI) of 2.89% required for LAP16, it would require at least 500 kg of base seed with 20% retention involving 27,300 farmers (Fig. 17). For LAP13, achieving DI of 7.31%, at least 700 kg of base seed with 25% retention will be needed which will involve 58,940 farmers. Little less than 600 kg base seed with 35% retention will ensure materializing the required DI (16.37%); for those 97,560 farmers would need to participate in demonstrations (Fig. 17). The results reveal that farmers' increased seed retention percentages, compared to base seed availability, will be more effective to curtail the LAP. This increased seed retention should ensure quality control in storage. Further interventions will include research-seed production-extension linkages, and large-scale training of farmers on quality seed production, processing and storage.

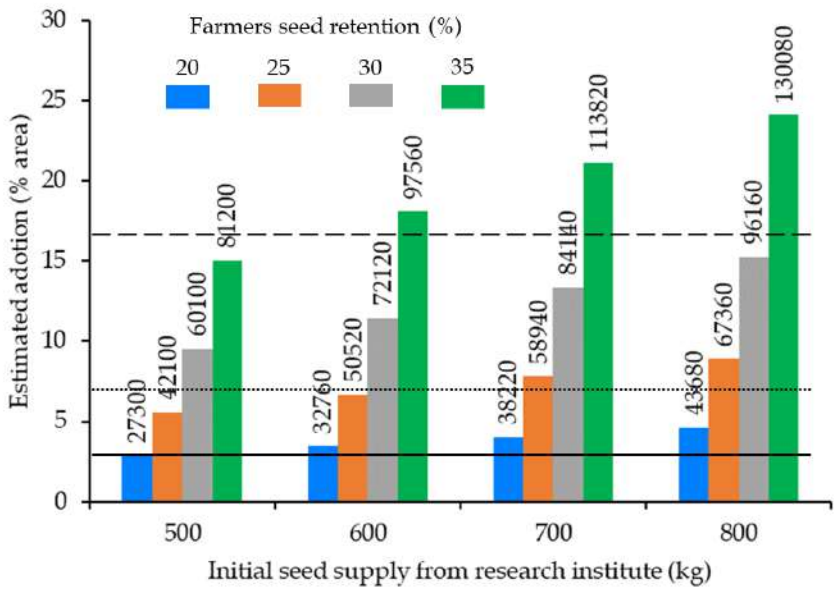


Fig. 17. AD4NRV model estimated 16 diffusion outcomes for a 'mega-variety'*, resulting from a combination of four-levels of two auxiliary variables: amount of base seed** available from research institute (500, 600, 700, and 800 kg) and farmers seed retention (20, 25, 30 and 35% of produced seeds). BRRI dhan29 was a test variety for this analysis which has the maximum adoption of 42% by area during Boro season. The solid, dotted and broken lines represent the required diffusion target (%), estimated from GRVA model at the end of three years of release. Each numeric value shown on top of a bar indicates the number of demonstration needed for achieving the estimated diffusion outcome.

* A variety is designated as a 'mega-variety' which, within its adoption cycle, receives significant area coverage (perceived as at least 25%) in a growing season.

** The seed to be used for demonstration, produced and supplied by variety releasing institute, during the releasing year.

Rice potential to ensure nutritional security

In Bangladesh, rice has enormously contributed to the food security. Rice farming will likely be attracted in future if the crop can be valued beyond its traditional use of a 'calorie provider'. Varieties that are high in quality, rich in nutrition, and capable of producing value adding product would be lucrative and preferable to stakeholders. Such non-traditional utilization of rice has least been studied in Bangladesh. In this study, we have developed a profile of officially released rice varieties developed by BRRI, as data available, under three broad attributes – quality, nutrition, and product diversity.

Among the tested varieties, nine were identified as rich in aroma (Fig. 18a and 18b), of which BRRI dhan34 has field adoption of 3.69% in T. Aman season, and BRRI dhan50 has 1.78% in Boro season. BRRI dhan50 is also graded as premium quality rice (PQR). There are four other varieties recognized as PQR; among those, BRRI dhan63 cover 1.07% of Boro rice area during 2019-20.

GER (Gama amino butyric acid enriched rice) has been recognized only in BRRI dhan31, IER (Iron enriched rice) in BRRI dhan84, and FSVA (Fat soluble Vitamin-A enriched rice) in BRRI dhan29; the latter variety has wide adoption (25.65%). Three varieties (BRRI dhan71, BRRI dhan77, BRRI dhan83) were found rich in QAER (Quality amino acid enriched rice), and three (BR16, BRRI dhan46, BRRI dhan69) in LGR (Low glycemic indexed rice); current adoption rate of these varieties is low (<1%) other than BR16 (1.20%). It may be noted that diabetic affected people would have preference for LGR rich varieties. Eight varieties (BR5, BRRI dhan37, 84, 87, 88, 90, 94 and 99) are antioxidant enriched (AER), but they are not adopted widely by the farmers. Five varieties (BRRI dhan75, BRRI dhan76, BRRI dhan77, BRRI dhan86, BRRI dhan87) possess QERB (Quality enriched rice bran), but their adoption is not fully scaled yet. The six (BRRI dhan70, BRRI dhan71, BRRI dhan75, BRRI dhan76, BRRI dhan77, BRRI dhan79) OER (Oryzanol enriched rice) are relatively newer and their adoption is yet to be fully explored in the field. Of the 7 WSV varieties (BR16, BRRI dhan28, BRRI dhan29, BRRI dhan36, BRRI dhan43, BRRI dhan48, BRRI dhan58), field adoption of all but BRRI dhan43 is high. Eight varieties (BRRI dhan42, BRRI dhan43, BRRI dhan62, BRRI dhan64, BRRI dhan72, BRRI dhan74, BRRI dhan84 and BRRI dhan100) have been identified as rich in zinc (ZER) but their adoption is poor. Of the ten identified protein rich (PRO) varieties, adoption is not high except BRRI dhan34; to be noted that this variety is also rich in aroma. The number of phosphorus and calcium rich varieties are relatively high (15 and 28, respectively). A few but not all of those varieties have good field adoption.

BRRI studies have identified product diversity in many varieties. For example, 25 varieties are suitable for energy-dense rice biscuits, 18 for flattened rice, 11 for popped rice, nine for puffed rice, 25 for rice biscuits, 25 for rice cake, 25 for rice dry cake and three for rice noodles (Fig. 18a and 18b). With few exceptions, varieties that possess inherent quality, nutrition and specific product diversity are not used for those purposes.

Rice production systems: The challenges and hopes

The broad challenges

Rice production environment of Bangladesh has been facing multidimensional challenges, as discussed briefly in our previous study (Kabir *et al*., 2015), which included population pressure and resource constraints.

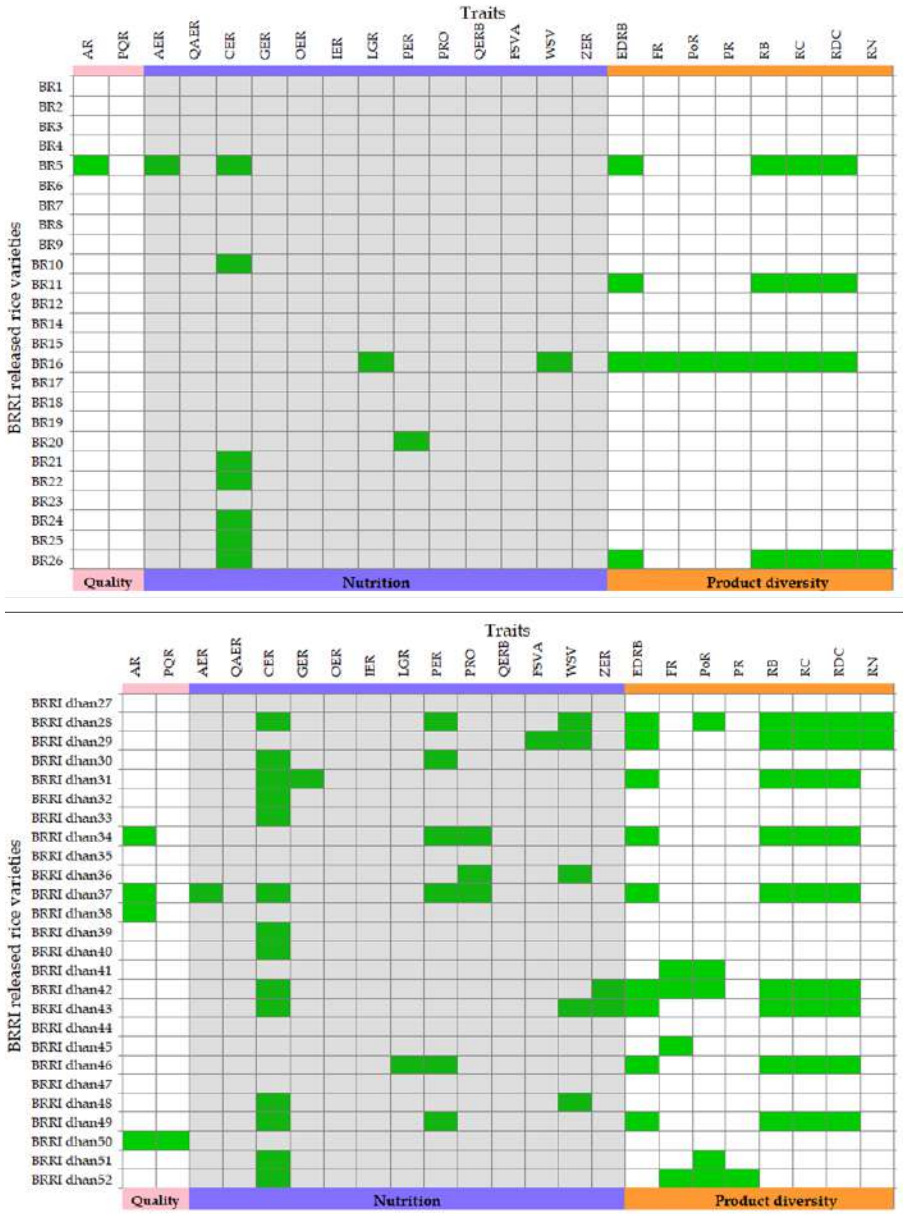


Fig. 18a. Quality, nutrition and product diversity characteristics of BRRI released rice varieties from BR1 to BRRI dhan52. AR, aromatic rice; PQR, Premium quality rice; AER, Antioxidant enriched rice; QAER, Quality amino acid enriched rice; CER, Calcium enriched rice; GER, Gama amino butyric acid enriched rice; OER, Oryzanol enriched rice; IER, Iron enriched rice; LGR, Low glycemic indexed rice; PER, Phosphorus enriched rice; PRO, Protein enriched rice; QERB, Quality enriched rice bran; FSVA, Fat soluble Vitamin-A enriched rice; WSV, Water soluble vitamin enriched rice; ZER, Zinc enriched rice; EDRB, Energy dense rice biscuit; FR, Flattened rice; PoR, Popped rice; PR, Puffed rice; RB, Rice biscuit; RC, Rice cake; RDC, Rice dry cake; RN, Rice noodles.

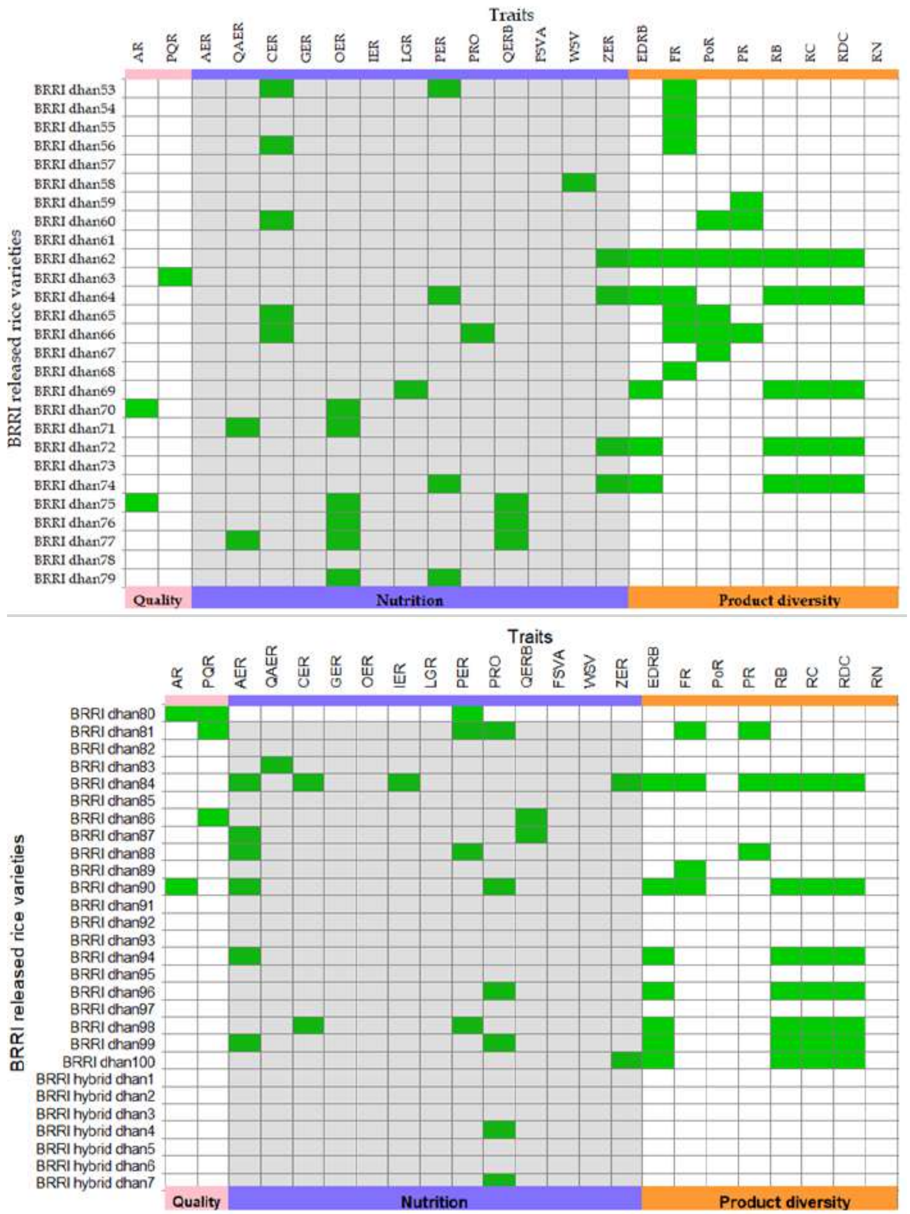


Fig. 18b. Quality, nutrition and product diversity characteristics of BRRI released rice varieties from BRRI dhan53 to BRRI hybrid dhan7. AR, aromatic rice; PQR, Premium quality rice; AER, Antioxidant enriched rice; QAER, Quality amino acid enriched rice; CER, Calcium enriched rice; GER, Gama amino butyric acid enriched rice; OER, Oryzanol enriched rice; IER, Iron enriched rice; LGR, Low glycemic indexed rice; PER, Phosphorus enriched rice; PRO, Protein enriched rice; QERB, Quality enriched rice bran; FSVA, Fat soluble Vitamin-A enriched rice; WSV, Water soluble vitamin enriched rice; ZER, Zinc enriched rice; EDRB, Energy dense rice biscuit; FR, Flattened rice; PoR, Popped rice; PR, Puffed rice; RB, Rice biscuit; RC, Rice cake; RDC, Rice dry cake; RN, Rice noodles.

Newer challenges are driving the country towards a changed reality day by day and drawing attention for enhancing efficiency, quality, and safety through mitigating risks and other impediments.

The volume of rice production in Bangladesh is dictated by requirements for human consumption and non-human utilization. Increasing population has been demanding more rice to produce year by year. On the demand side, quality has been a rising issue that incorporates nutrition and food safety (Fig. 19). Meeting SDG, which the government is keen to achieve, is also added to the demand profile.

The rice production of Bangladesh has been constrained by limitation in resources and vulnerability in climate. The scope of utilization of natural resources, such as land and water, has narrowing both in terms of quantity and quality. Population pressure also exerting negative effect on availability of natural resources. Availability of labour in agricultural activities, including rice, has also been an issue in the last three decades. Bangladesh is one of the hot spots to climate vulnerability and is highly exposed to extreme weather events. Every year the country faces several extreme weather events has already been fighting to combat environmental risk and their impacts (WB, 2013).

Market risk frequently creates uncertainty in the rice production systems in Bangladesh. The price volatility has been a frequent threat to sustained rice cultivation. On the other side, the scope and profitability of many non-rice crops are increasing day-by-day. It has become an urgency to guarantee farmers' profitability for maintaining regularity in rice cultivation.

Bangladesh still experiencing low rice productivity due not been able to applying appropriate management options in adequacy and on time. Studies identified knowledge gap as one of the key factors for inadequately addressing crop management requirements.

Bangladesh rice sector is affected by various uncertain indirect crises, financial turmoil, political upheaval, and externalities. For example, in recent times Rohingya crisis, COVID-19 pandemic, and negative income shock are threatening the progress of the rice sector. Other challenges include subsistence type farming, small and uneconomical farm size, aging of farmers, low attraction of youth in agriculture, low agricultural diversification, and low profitability of rice farming.

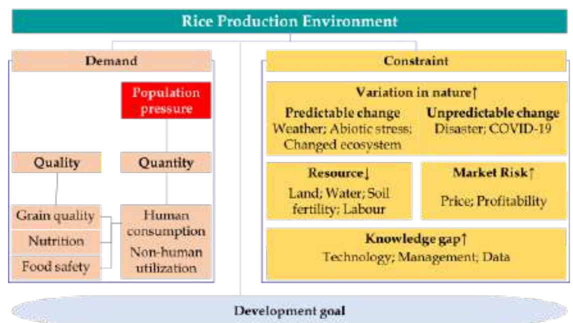


Fig. 19. A sketch of current rice production environment in Bangladesh showing demands and constraints.

The hopes

Yield progress and availability of rice area

The progress in yield, expressed as clean rice, in Bangladesh has been steady. The estimated clean rice yield has been found increasing linearly (Fig. 20) according to Holt-Winters seasonal method (Holt, 1957; Winters, 1960), which giving a strong indication that genetic potential of varieties is likely to increase. This relationship projected the yield at 95% confidence interval for 2030 as in the range of 3.06 – 4.53 t ha^{-1} and for 2050 as 3.00 – 6.56 t ha^{-1}; the figures of GenPot values what we set in this study sit within the ranges, and also supported by Salam *et al.* (2019a).

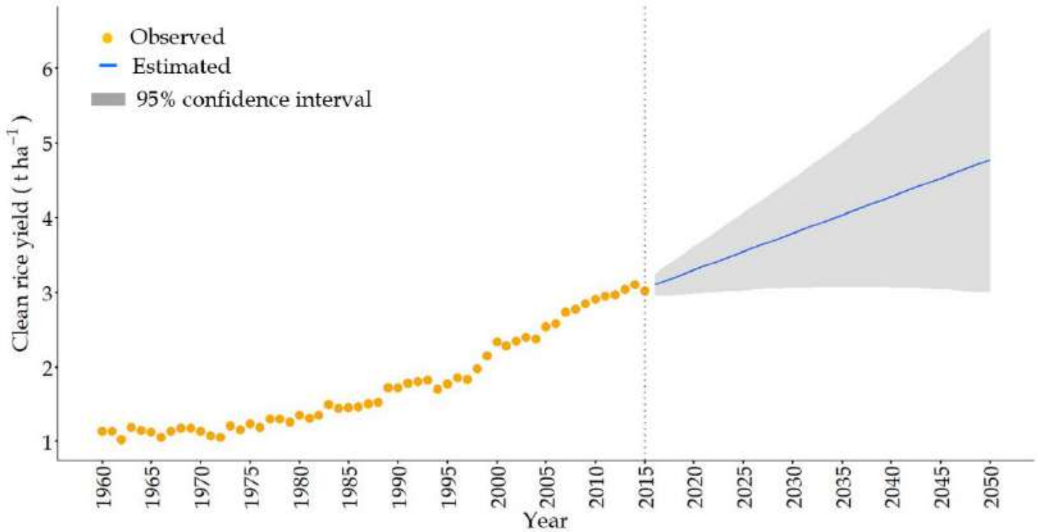


Fig. 20. Historical trend (1960 – 2015) and estimation of future (2016 – 2050) clean rice yield in Bangladesh.

Crop production increase is classically addressed either through vertical dimension i.e., yield, or horizontal dimension i.e., cultivation area. Bangladesh has bright prospect of utilizing both the dimensions for increasing rice production estimated for the period 2020 – 2050. We have shown our analyzed results above on how the country will be capitalizing genetic improvements for continued rice yield advantage. Bangladesh has three main rice growing seasons – Aus, Aman (principally transplant Aman (T. Aman)) and Boro. Our estimation shows the area under Aus, the early monsoon rice, will be heading around 1.45 – 1.50 M ha in 2030, 1.50 – 1.60 M ha in 2040 and 1.60 to 1.70 M ha in 2050 from 1.25 to 1.30 M ha in 2020. Together with the increasing yield prospect and steady improvements in crop management, the production of clean rice in Aus season in 2030, 2040 and 2050 has been estimated in the range of 4.82 – 4.99 MT, 6.07 – 6.47 MT and 7.62 to 8.10 MT, respectively. Similarly, rice production, through both vertical and horizontal dimensions, has conservatively estimated in the range of 16.48 – 16.77 MT, 18.00 – 18.53 MT and 17.09 – 20.34 MT in Aman season, and in the range of 21.76 – 21.99 MT, 22.91 – 23.65 MT and 22.49 – 25.28 MT in Boro season during 2030, 2040 and 2050, respectively. Taken all together, Bangladesh would be able to produce 43.06 – 43.74 MT of clean rice in 2030 from 12.00 – 12.20 M ha of gross rice area, 46.97 – 48.66 MT of clean rice in 2040 from 11.85 – 12.27 M ha of gross rice area and 47.20 – 53.72 MT of clean rice in 2050 from 10.78 – 12.35 M ha of gross rice area. Year-by-year estimated area, yield and production of clean rice in three seasons have been presented in Appendix 1. It is to be noted that the stakeholders to meet the season-wise rice production area in the estimated ranges to ensure the production estimates. Those estimated target area and production figures will ensure to maintain future rice security of the country; any increase in target area and production over the estimates will further strengthen the rice reserve in the national food basket.

Resisting the effect of climate change

The evidence relating climate change and rice productivity in Bangladesh at macro-level is limited. In this study, we attempted to find a relationship between seasonal potential evapotranspiration and yield of Boro rice in specific locations, and anomalies in annual temperature and rice nationally.

Relationship between potential evapotranspiration and rice yield

The relationship between evapotranspiration and Boro rice yield was assessed based on historical (1981-2016) climatic parameters (e.g., maximum and minimum air temperature, relative humidity, wind speed, and bright sunshine hours) induced changes in ET_0. During the period of 1981 to 2016, the linear decrease in ET_0 @ -0.0164 mm day^{-1} had been significant ($Y = 36.709 - 0.0164*Year$, $R^2 = 0.45$; $N = 36$, $P<0.001$), indicating climatic change had taken place in the districts (Fig. 21). The decreased ET_0 could be explained by the combined effect of decreasing solar radiation (derived from bright sunshine hours) and wind speed and increasing mean air temperature and relative humidity of the study regions. On the other hand, clean rice yield had increased linearly and significantly ($Y = -116.586 + 0.0599*Year$, $R^2 = 0.95$; $N = 36$; $P<0.001$). Between the two variables, the correlation was significantly negative ($r = -0.658$; $N = 36$; $P<0.001$).

Relationship between temperature and rice yield

During the period of 1961 to 2016, the linear increase in temperature anomaly @ 0.012 ^oC had been significant ($Y = -23.23 + 0.0118*Year$, $R^2 = 0.37$; $N = 56$, $P<0.001$), indicating temperature variability had taken place in Bangladesh (Fig. 22). On the other hand, clean rice yield had increased linearly and significantly ($Y = -78.107 + 0.0396*Year$, $R^2 = 0.92$; $N = 36$; $P<0.001$). Between the two variables, the correlation was significantly positive ($r = 0.613$; $N = 36$; $P<0.001$). In the scenario of overall Bangladesh, the historical (1961-2016) temperature anomaly was positively related to clean rice yield in Bangladesh (Fig. 22).

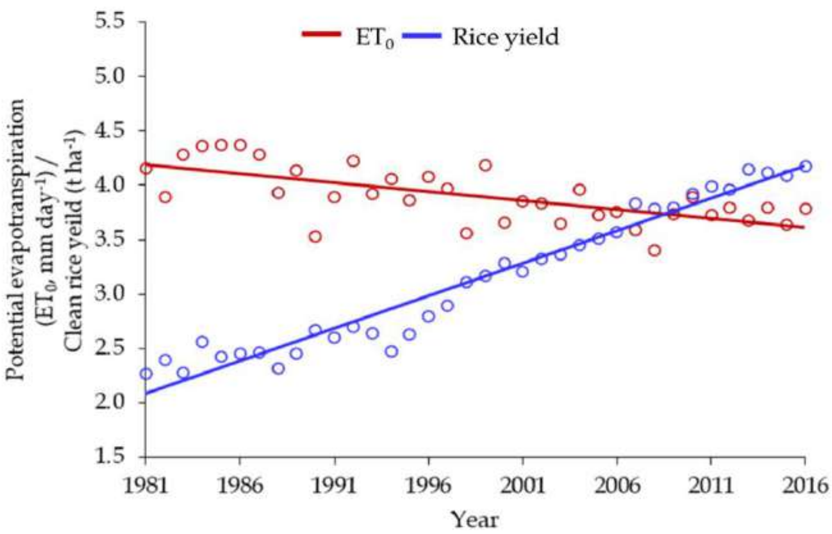


Fig. 21. Trend in potential evapotranspiration (ET_0) and clean rice yield during Boro season of 1981-2016. Data of both variables are averages for four administrative districts of Bangladesh – Faridpur, Khulna, Mymensingh and Rajshahi.

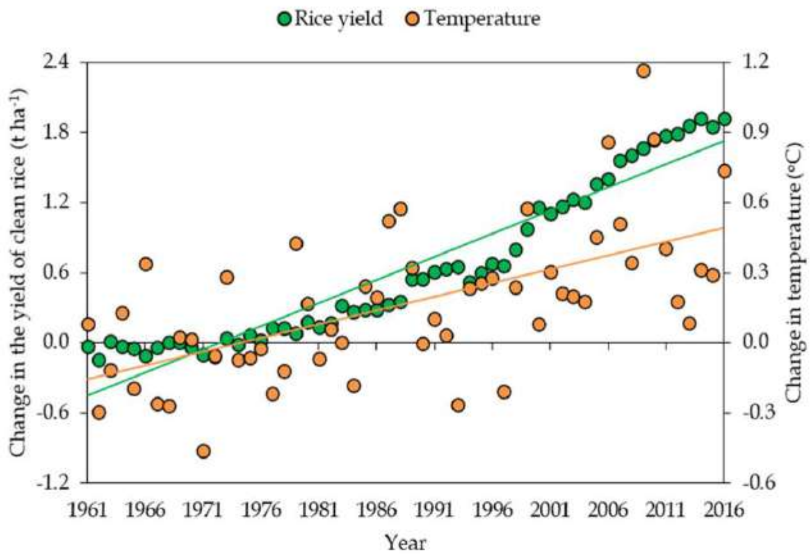


Fig. 22. Relationship between the variability in yearly anomalies of temperature and clean rice yield in Bangladesh during the period of 1961-2016.

Rice Sustainability

A conceptual framework for sustainable rice production is presented in Figure 23. The framework has four dimensions. The Dimension-1 (Economic sustainability) consists of three sub-indicators - farm output, net farm income, and economic resilience.

The status of soil degradation, water availability, fertilizers and pesticide management and biodiversity-supportive practices are the sub-indicators of Dimension-2 (environmental sustainability). Three sub-indicators represent Dimension-3 (social sustainability) - the off-

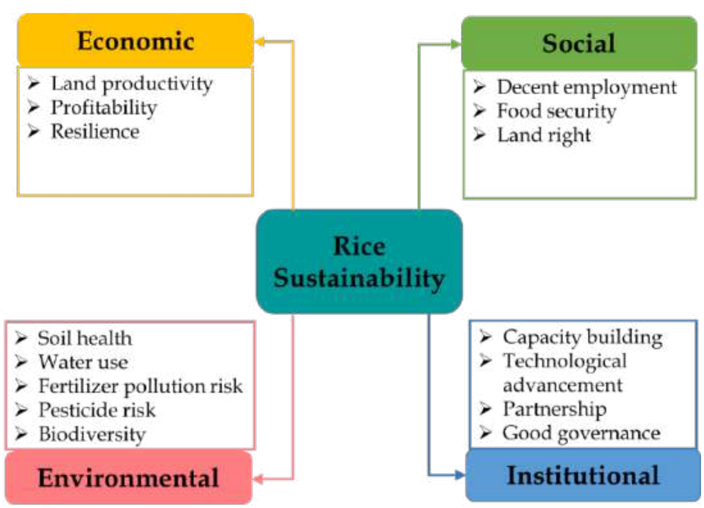


Fig. 23. A conceptual framework for sustainable rice production in Bangladesh.

farm employment opportunity, scale of food insecurity and malnutrition experience, and tenurial rights to land. Finally, the capacity building, technological enhancement, partnership development, and good governance are grouped in Dimension-4 (institutional sustainability) as sub-indicators. The sub-indicators of the sustainability dimensions were measured using published and unpublished data from literature, secondary sources, experiments, and field surveys.

Economic dimension

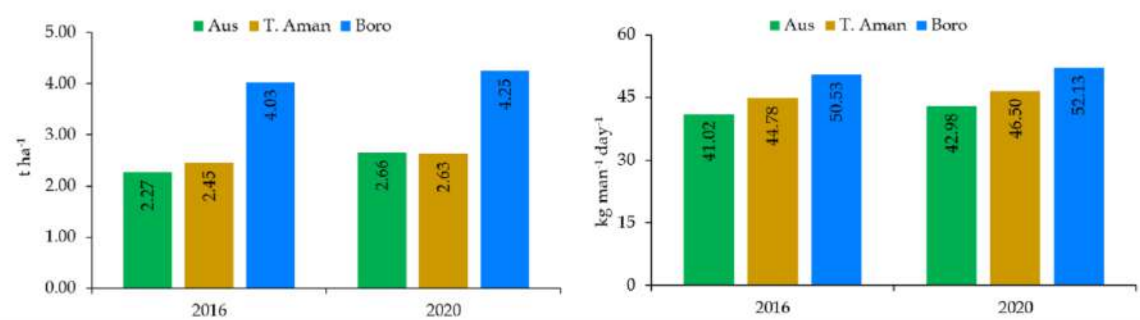
Land productivity

Land and labour productivity are presented in Figure 24. The per hectare productivity of land under Aus, T. Aman and Boro rice was higher by 7.3%, 17.2% and 5.5%, respectively in 2020 compared to SDGs base year (2016). Besides, the rate of increase of labour productivity per work-day of Aus, T. Aman and Boro rice was higher by 3-5% in 2020 compared to 2016 (Fig. 24).

Profitability and risk

Gross income or margin (per hectare) of Aus, T. Aman, and Boro rice was found increased by 7.1, 4.8 and 10.2% in 2020 from the base year (Fig. 25a). Increased farm income resulted from decreased production costs. This cost reduction occurred due to increased adoption of farm machineries and receiving better rough rice prices. Figure 25b shows that the semi-mechanized and mechanized cultivation reduced per hectare cost of rice production by BDT 23,203 and BDT 42,664, respectively.

However, rice farming in Aus, T. Aman and Boro season has been highly risky (i.e., probability of having negative net income is very high) under the current market and environmental conditions due to high seasonal variation in yield and price. Nevertheless, the probability of having a negative net income of rough rice decreased to zero under the extrapolated yield and price in 2030, indicating that rice cultivation irrespective of seasons will be economically sustainable subject to meeting the targeted Ref-MinPro, and ensuring farmers' access to projected price (Kabir *et al.*, 2020). In addition, improved profit would be achieved through development of farm-to-market linkages and increase resource use efficiency in the area of irrigation, fertilizer management and labour.



a. Production per unit of land   b. Production per unit of labour

Fig. 24. Productivity of land and labour in Aus, T. Aman and Boro season in Bangladesh. Authors' calculation based on DAE, 2020 and field survey, 2020 data.

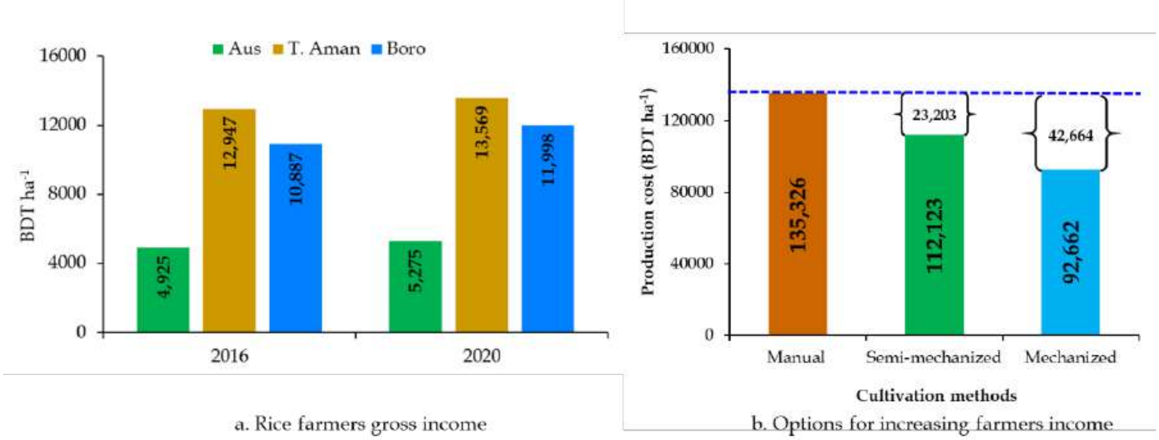


Fig. 25. Gross income from rice cultivation and options for further increasing farmers' income in Bangladesh. Authors' calculation based on field survey data.

Resilience

The abiotic stresses, including salinity, submergence, drought and biotic agents (e.g., insects and diseases) are potential production risk factors for natural weather dependent rice production in Bangladesh. Those stresses play a vital role in the seasonal variation in rice productivity. Therefore, increased adoption of stress-tolerant rice cultivars may notably alleviate the production risk. Figure 26 shows that the adoption of salinity, submergence and drought-tolerant rice cultivars were 35%, 26% and 12%, respectively, which increased rice production by 10, 9, and 8% for respective stress-tolerant areas. This success has achieved through applying climate smart technology and practices such as ecology suited seed production, short duration variety, mechanization, and knowledge sharing and training.

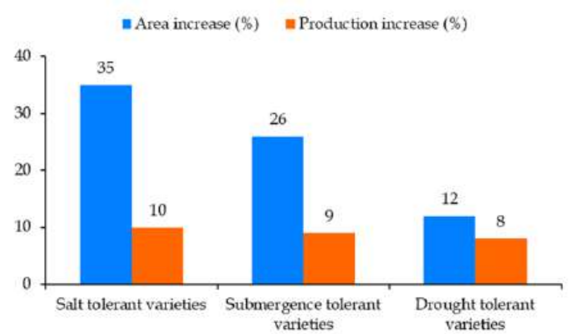


Fig. 26. Area coverage of the stress tolerant rice varieties and their contribution to the national food basket. Prepared by authors based on data from DAE.

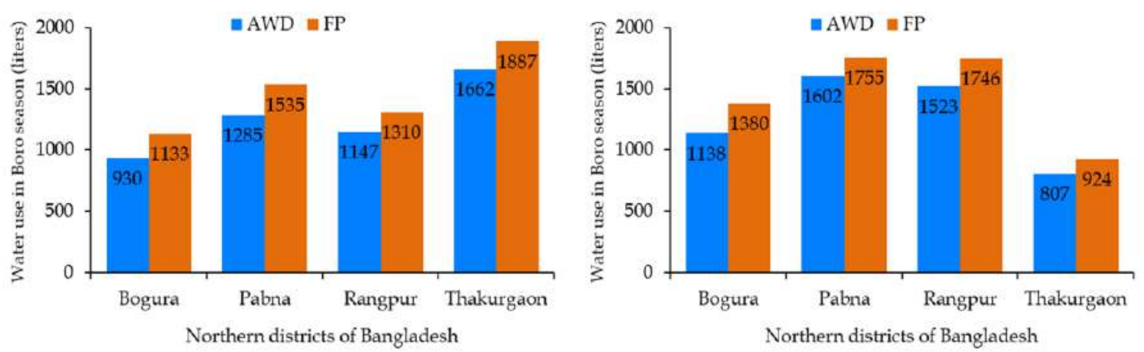
Environmental dimension

Soil health

The results of a long-term experiment (33 years) confirmed that the negative net carbon balance in the fields adversely affected, consequently deteriorated soil health due only to chemical fertilizer dependent nutrient management for rice crops in Bangladesh. As a result, soil of about 40% of the net cropped area of the country is under health risk (Haque *et al.*, 2019). The incorporation of (i) 20 cm of rice straw into the soils of the rice-rice cropping patterns, (ii) Sesbania (*S. rostrata*) cultivation during the fallow period and incorporation into the soil, and (iii) increased application of organic fertilizers (such as, kitchen waste) and farmyard manure in the crop fields may reduce soil health risk (Details in Haque *et al*. 2020).

Water requirement for irrigated rice

Figure 27 presents the water requirement for producing a kilogram of rough rice both in alternate wetting and drying (AWD) method and farmers' practice (FP). The water consumption of rice crops in the dry season (Boro) depends on soil texture, variety, and seasonal variation in the temperature and rainfall between the years. The average water requirement of irrigated Boro rice per kilogram vary in the range between 807 – 1,887 liters depending on the locations; this variation occurs due to variation in soil types, transplanting time and growth duration of the rice cultivars. However, the water consumption of the irrigated Boro rice might decrease under increased adoption of water-saving technologies.



a. Water use in Boro rice cultivation, 2016-17 b. Water use in Boro rice cultivation, 2017-18

Fig. 27. Water requirement for producing a kilogram of rough rice. AWD and FP denote for alternate wetting and drying, and farmers' practice, respectively. Source: Adopted from BRRI (2019).

Chemical fertilizer and pesticide risk

There has been significant gap between farmers' practices and scientific recommendations of fertilizer and pesticide management for the rice crops; this is because of inadequate knowledge of farmers about the recommended practices, and awareness about the harmful effect of applied practices on soil and human health (Miah *et al*., 2019; Ali *et al*., 2020). This gap is responsible for current yield loss in the country, and human and soil health risk. Improvement of farmers' (i) knowledge about recommended fertilizer and pesticide management for rice crops and (ii) awareness about harmful consequences of improper fertilizer and pesticides management on human and soil health through providing training to farmers, and demonstration across the country may substantially reduce the yield gap and health risk for both the soil and human.

Biodiversity

The decreased biodiversity of rice cultivars globally is an adverse consequence of the development of plant breeding techniques and extension programme for the adoption of higher yield potential modern cultivars to meet up the increased demand of rice grain for the growing population. Besides, biodiversity in the fauna in the rice fields also decreased substantially in the globe due to the increased adoption of chemical methods for controlling harmful arthropods and pathogens in rice crops. However, continuing cultivation of some higher yield potential and special traits cultivars in particular aromatic rice in some areas and increased extension programme for adoption of biological and mechanical controlling methods of pest may improve ecological balance through increasing biodiversity. Especially, the biodiversity-supportive practices such as perching, eco-agriculture (Ali *et al*., 2019), and restricting the application of pesticides within 30 days of transplanting, need to be implemented in rice fields to conserve biodiversity in Bangladesh. Furthermore, maintaining rice genebank and improving yield of traditional varieties will contribute to biodiversity conservation.

Social dimension

Decent employment

Agriculture, in particular, rice farming, generates employment of 40.60% of the total labour force in the country (BER, 2019). Gender inequality still remains in the wages and earnings of agricultural labourers (Fig. 28). We should minimize gender gap in agriculture through effective policy intervention. The employment opportunity in agriculture sector might be increased further in the future due to the increased intensity of cropping in the country. Besides, the development of entrepreneurship on producing, marketing, maintenance and custom hire-based rental service of farm machineries as well as operating the farm machineries may increase the employment opportunity in the country. Moreover, a large number of people are currently employed in the value-adding sector of rice and employment opportunities in the sector will further increase in future as well.

Food security

The rice self-sufficiency ratio (RSSR) has been around 68% immediately after independence. Since then, it started increasing slowly (Fig. 29). During 1999, the RSSR sharply jumped to over 92%. Towards the beginning of the current decade, Bangladesh crossed the self-sufficiency line (100%). The dataset of the Food Planning and Monitoring Unit (FPMU) of the Ministry of Food, Government of Bangladesh (http://fpmu.gov.bd/fpmu-database/0103.htm, accessed

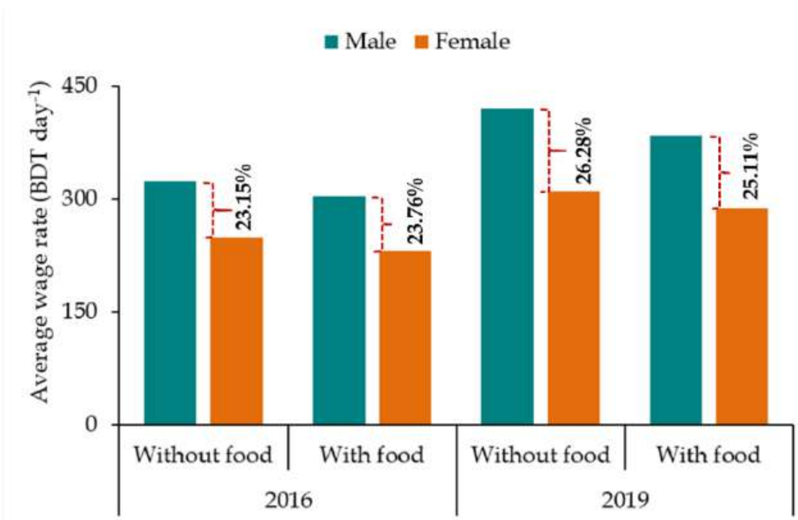


Fig. 28. Wage of male and female agricultural labourers in Bangladesh under two packages: food supplied ('with food') and no food supplied ('without food') by landlords. Also shown the wage gap between two genders. Source: Prepared by authors based on data from BBS (2020).

on 17 November 2020) showed continued positive balance of foodgrain since 2007-08, a similar timing and trend estimated in our study. It is then evident from the figure that the country has remarkably transformed herself from so called 'bottomless basket' to 'full of food basket'. Although Bangladesh is in a strong position of maintaining self-sufficiency in rice, year-to-year variability still exists. Besides availability, there are other components of food security, which this study did not cover. Efforts to be made to highlight all the additional components (such as affordability, nutrition and stability) to comprehensively address food security of Bangladesh.

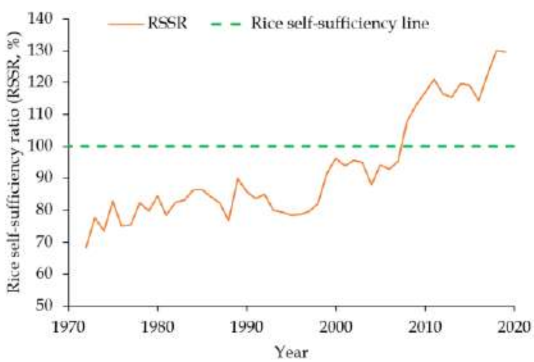


Fig. 29. Rice self-sufficiency ratio in Bangladesh during 1972 to 2019.

Land right

The current system of land tenure is based on the Land Reform Act of 1950, which abolished the British colonial landlord system. In Bangladesh, three types of tenurial arrangements are found, such as owner, owner-cum-tenant, and pure tenant operators. At present, about 56.92, 38.55, and 4.53% of the total farm holdings are managed by owner (who cultivate their own land), owner-cum-tenant, and tenant operators, respectively. The historical trends (1960-2019) show that the owner operators have been decreasing significantly, whereas the owner-cum-tenants have been increasing sharply (Fig. 30). Productivity is closely linked to the land tenurial arrangements. Rice productivity of tenant operated farms found lower than owner-operated farms due to insecure land rights and less contribution of property owners in production cost (Islam, 2017). However, the contractual arrangements of the tenancy have been classified into two groups, for example, crop-share and fixed-rent tenancy. Surprisingly, the productivity and efficiency are higher on fixed-rent tenancy than on the crop-share tenancy (Nasrin and Uddin, 2011; Islam and Fukui, 2018). Therefore, development law for land tenurial arrangement for ensuring the right for operating the land for a specific period and rental fees per year may secure the right to the land of tenant farmers, consequently, rice productivity would increase.

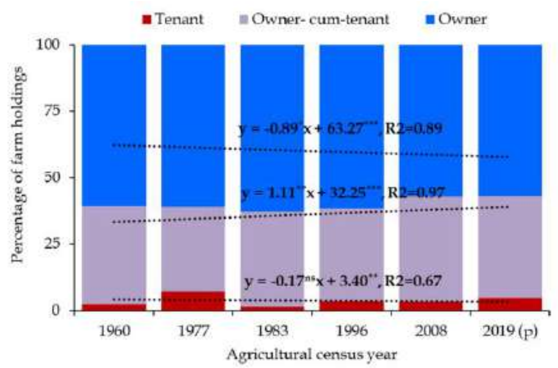


Fig. 30. Historical land tenurial arrangement in Bangladesh. Note: 'p' for provisional, '*' for 10% level of significance, '**' for 5% level of significance, '***' for 1% level of significance, and 'ns' for not significant. Prepared by authors based on data from different issues of Agricultural Census, Bangladesh.

Institutional capacity

The skilled manpower is a cornerstone for developing higher yield potential and stress-tolerant rice cultivars, component technologies, and disseminating the technologies to the end-users. Therefore, institutional capacity needs to be increased by increasing the skills of its manpower. Thus, the arrangement of short term and long-term training in the country and overseas for improving the skills of manpower of the institutes is a must. Besides, development of national and international partnerships is very important to minimize the gap between scientists' achievement and farmers' output. On top of that, adequate investment would be needed to develop enhanced research facilities and manpower. Moreover, good governance will ensure transparency, accountability, participation, and inclusion to all for achieving the development agenda 2030 and beyond.

Overcoming market inequity and price instability

Figure 31 shows that farmers' share of consumer price decreased to 41% in 2019 from 65% in 2000, indicating that the influence of producers in the rice market has been decreasing over time. The cost-benefit analysis shows that, while the rice growers pay higher cost of production, the value-adding stakeholders reap the maximum benefit. This indicates that there have been notable discrepancies in the allocation of consumers' price share between the stakeholders. This inequity might be alleviated by setting the maximum consumer price share limit by 55%, 25%, 7%, and 13% for producers, millers, paddy traders and rice traders, respectively. This will be ensured through strengthening the value chain with strong farm-to-market linkage, rural infrastructure, and information to improve the market system.

An ensured access to remunerative and stable market price is a necessity for sustainable rice production and productivity, since, the rice market is inherently unstable, and the growers often inflict unexpected income losses. Thus, a Commission faor Agricultural Costs and Prices (CACP) is proposed to form through restructuring the Department of Agricultural Marketing (DAM) as an attached office of the Ministry of Agriculture to (i) alleviate the existing scrupulous market deals between the value-added stakeholders, and (ii) ensure a fair price to the producers. The CACP will be mandated to recommend grain type-wise minimum support prices (MSPs) of rough rice to incentivize farmers for increasing productivity and overall grain production in the country. The CACP will determine the grain type-wise MSP for harvesting (wet rough rice) and post-harvesting (dry rough rice) period by considering (i) demand and supply; (ii) cost of production; (iii) price trends in domestic and international markets;

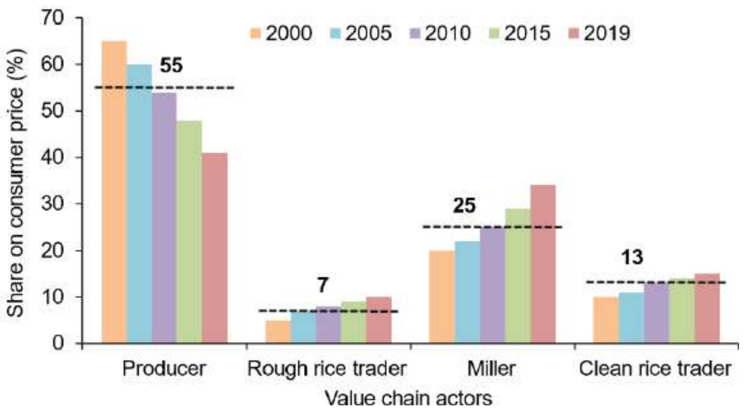


Fig. 31. Change in the share of rice price during 2000 – 2019 by the value chain actors accumulated into consumer's price. The numbers above broken lines indicate the lower thresholds for respective value chain actors.

(iv) inter-crop price parity; (v) terms of trade between agriculture and non-agriculture; (vi) a minimum of 20 percent as the margin over the cost of production; and (vii) likely implications of MSP on consumers of that product. The grain type-wise minimum support price is a guaranteed price of rough rice at the local market during harvesting and post-harvest period to protect farmers from unexpected losses due to price falls. In other words, MSP is determined to set a floor below which the market prices cannot fall. The government will declare the grain type-wise MSP for wet and dry rough rice based on the recommendation of CACP before the planting season of crops so that the growers could make decisions for the allocation of land considering the potential intensive of the crops based on the support price. The government will purchase the rough rice in case the market price falls below the announced minimum price either because of higher production or because of scruples deal of value-adding stakeholders.

Besides, a triangular procurement model might be developed for farmers' ensuring access to MSP and shifting the government rough rice procurement benefit to real farmers, including small and marginal from the market intermediaries (Fig. 32). The CACP and local administrative unit will function as a decision-making unit and an implementation unit, respectively in the procurement model. PPC will be established at union-level where procurement activities will be carried out.

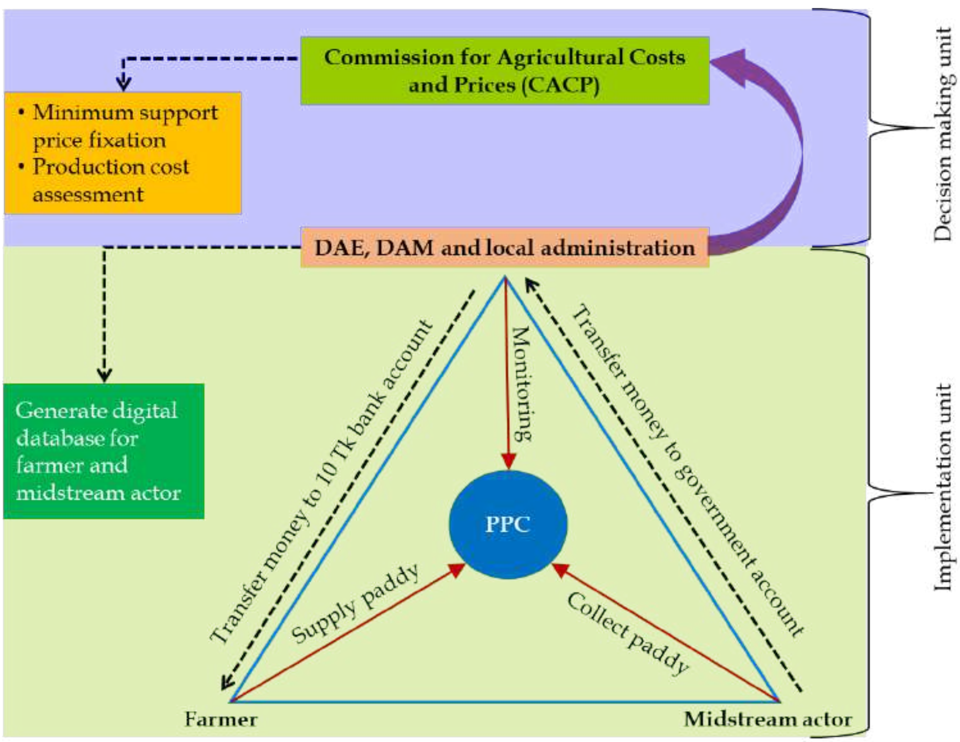


Fig. 32. A proposed concept of triangular rice procurement system for Bangladesh. DAE, DAM and PPC denotes for Department of Agricultural Extension, Department of Agricultural Marketing, and Public Procurement Center, respectively. The initial concept was presented by the lead author in the International Rice Congress 2018 (IRC2018) held in Singapore during 14 - 18 October 2018.

Firstly, the decision-making unit e.g., the CACP will prepare a district-wise database on basic information, including farm size and mobile number of farmers and value-adding stakeholders; the database will be updated before each cropping season. The Department of Agricultural Extension (DAE) and local administration will assist the commission to develop the database. As discussed, the government will declare the floor price of rough rice for the local market in the harvesting season as suggested by the CACP.

Secondly, the CACP will broadcast the grain type-wise MSPs at harvesting (wet rough rice) and post-harvesting (dry rough rice) period and the list of local level procurement centers in mass media. Besides, they will pass the information to enlisted producers and value-adding stakeholders, including traders and millers. The producers, traders and millers will assemble at PPC for marketing the rough rice at the government declared grain type-wise MSPs at harvesting and post-harvesting season. Besides, the government will procure rough rice from the procurement location at MSP. It may be noted that the government has to develop infrastructural facilities for drying the rough rice that was procured from a local level procurement place.

Finally, the traders and millers will transfer the grain type-wise MSP of the rough rice at harvesting and post-harvesting period to the government account through online/mobile banking with farmers' information, including name, mobile number and bank details. The money will be automatically transferred to the respective farmers' bank account from the government account. The bank will send a text message to farmers' mobile number as confirmation of depositing the money to their account. Similarly, the value of the government procured rough rice from the local procurement center will also be directly paid to the respective farmers account for ensuring accountability. An inter-ministerial monitoring team and the CACP personnel will regularly monitor the rice market.

Key interventions

In order to materialize the DRP framework, 22 key interventions have been proposed across the three wings (Table 3). The state-of-art methods and tools will be employed for varietal development, capacity building of scientists, extension agents, farmers, influencers and value chain actors will be undertaken, and public private partnership will be developed, nurtured and maintained in research and development (R&D) across the wings. Special efforts will be made to increase input use efficiency in the area of irrigation, fertilizer management and labour, while digital technologies will be used for breeding automation, data collection and processing, market information, robotics and technology inventory. We plan to develop synthesized research delivery system and find out adequate investment in research and development across the three wings. Rice management will gain efficiency and profitability through precision agriculture using high tech solutions in the fields of soil, water and pest-disease control together with deploying routine surveillance systems and designing early warning system (EWS); both surveillance and EWS will also contribute to strengthen market system for farmers and consumers. Mechanization will be extended by providing incentive and support to the farmers, and by inventing and/or adapting for scale-appropriate machineries for transplanting, harvesting and post-harvest operation.

Incentives will also encourage farmers to adopt new and smart management technologies such as one-in-all multi-nutrient essential

Table 3. A list of key interventions to implement the proposed DRP framework.

Sl. no.	Key intervention	Wing-1				Wing-2	Wing-3	
		Pillar 1 (GenPot)	Pillar 2 (ManPot)	Pillar 3 (SpacePot)	Speedy adoption	Mechanization	Nutrition	Market
1	Varietal development using state-of-art methods and tools	■						
2	Agro-ecology /zone specific / growth stage-based technology design	■	■			■	■	
3	Synthesized research delivery system	■	■	■	■	■	■	■
4	Irrigation infrastructure development			■				
5	Increase input use efficiency		■			■		
6	Precision agriculture using high tech solutions		■					
7	Early warning system based agro-advisory		■					■
8	Buffer input stock zone for stress management		■	■				
9	Improvement of the rice-based system productivity			■				
10	Farmer-based speedy seed multiplication and dissemination system				■			
11	Scale-appropriate mechanization for transplanting, harvesting and post-harvest operation					■		
12	Use of digital technologies	■	■			■	■	■
13	Incentive and support to farmers to adopt new technologies		■			■		
14	Monitoring and surveillance		■					■
15	Public private partnership in research and development	■	■		■	■	■	■
16	Establishment of commission for agricultural cost and price							■
17	Farm-to-market linkage							■
18	Adequate investment in research and development	■	■	■	■	■	■	■
19	Capacity development	■	■		■	■	■	■
20	Agro-processing and value addition						■	■
21	Long-term storage facility development for enhanced profit							■
22	Commercialization of rice farming	■					■	

Note: 'DRP' represents doubling rice productivity, 'GenPot' denotes for enhancing genetic potential, 'ManPot' for reducing yield loss, 'SpacePot' for exploring the unexplored spaces. Market is represented for 'fair price' in the DRP framework. The filled colour indicates the targeted interventions in the respective wings

fertilizer package for rice. To make the technologies attractive and adoptable to farmers agroecology and/or zone-specific and/or growth stage-based technology will be designed. Newer spaces for rice will be ensured by developing irrigation infrastructure, and stress will be managed by creating buffer input stock zone. Variety adoption will be speeded up by creating farmer-based speedy seed multiplication and dissemination system. A congenial rice market environment will be developed through the establishment of 'commission for agricultural cost and price', farm-to-market linkage, facilitating agro-processing and value addition, and commercialization of rice farming. The latter two interventions will also benefit nutritional improvement efforts. This paper also proposes activities to improve rice-system productivity in Bangladesh.

CONCLUSION

Potentially, rice production in Bangladesh can be increased to 46.90, 54.09 and 60.85 MT by the year 2030, 2040 and 2050, respectively, from the 2015 baseline of 35.29 MT through the combined successful contribution of three pillars of DRP framework – yield improvements by enhanced genetic potential (Pillar 1, GenPot), reduction in existing yield loss (Pillar 2, ManPot) and production increase by exploring unexplored spaces for rice (Pillar 3, SpacePot). Pillar 1 and 2 will enhance production by increasing productivity, while Pillar 3 will add extra rice to the production by expanding area. The country will be a 6.50 MT, 10.29 MT and 13.65 MT surplus in rice production, respectively, in 2030, 2040 and 2050 if we could implement the DRP framework successfully. Besides, labour productivity will double by 2029, meeting the SDG goal, through scale-appropriate mechanization backed up by estimated fair price. By realizing research and extension initiated needful 'diffusion intensity', i.e., the area coverage of the concerned variety at the end of three-year diffusion period, will curtail the 'length of adoption peak' of rice varieties resulting speedy achievement in production target. To achieve the rice production targets, efficiency, resilience and sustainability around the three pillars of DRP framework to be ensured. Thus, policy supports are needed for ensuring implementation of highlighted nine points: (i) strengthening demand-driven research on variety development for constraint environments, and nutrition enrichment, (ii) developing and disseminating field-adoptable management across the 17 rice growth stages, (iii) increasing mechanization on transplanting and harvesting operations, (iv) designing special extension approach for successful intensifying rice cropping in the five unexplored spaces, (v) implementing farmer-based intensive speedy seed multiplication and dissemination system, (vi) establishing input buffer stock terminals to mitigate externalities, (vii) establishing commission for agricultural costs and prices, (viii) exploring options for accommodating surplus production such as long-term storage and exporting, (ix) publicizing and market development for rice-based products through public-private partnership.

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AUTHORS' CONTRIBUTIONS

MSK, MUS, MARS, and MAAM generated idea; MSK and AKMSI coordinated the project; MUS, MARS, and MAAM developed methodology; MSK, MUS, MARS, and MAAM provided scientific insights; MUS, MARS, MAAM, MCR, MBH, HBS, AC, MN, KMI, MSH, MKAB, BK, MSR, MMH, MTK, MPA, SMHAR, PLB, ESMHR, and NMFR gathered data; MUS, MARS, MAAM, and MCR carried out analysis and synthesis; MUS, MARS, MAAM, and MCR did the writings for all versions of the manuscript; MSK, BN, MJK, MSR, MPA, and SMHAR performed critical review and editing; All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

A version of the paper was published in a book "Doubling Rice Productivity in Bangladesh" in 2020 by the Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh to commemorate BRRI's 50th anniversary. The Bangladesh Rice Journal has prior knowledge of the book publication and does not see any conflict of interest.

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Appendix 1. Estimated area, production and yield targets of rice in Bangladesh by rice growing season during 2020 to 2050.

Year	Area (M ha)				Production (MT)				Yield (t ha^{-1})		
	Aus	Aman	Boro	Total	Aus	Aman	Boro	Total	Aus	Aman	Boro
2020	1.25 - 1.30	5.85 - 5.90	4.70 - 4.75	11.80 - 11.95	3.26 - 3.39	14.94 - 15.07	19.65 - 19.86	37.85 - 38.31	2.60	2.55	4.18
2021	1.27 - 1.32	5.85 - 5.90	4.71 - 4.76	11.82 - 11.98	3.40 - 3.53	15.10 - 15.24	19.86 - 20.07	38.36 - 38.84	2.68	2.58	4.22
2022	1.29 - 1.34	5.84 - 5.90	4.71 - 4.76	11.84 - 12.00	3.55 - 3.68	15.25 - 15.41	20.07 - 20.28	38.87 - 39.37	2.75	2.61	4.26
2023	1.31 - 1.36	5.84 - 5.90	4.72 - 4.77	11.86 - 12.03	3.69 - 3.84	15.41 - 15.58	20.28 - 20.49	39.38 - 39.91	2.82	2.64	4.30
2024	1.33 - 1.38	5.83 - 5.90	4.72 - 4.77	11.88 - 12.05	3.85 - 3.99	15.56 - 15.75	20.49 - 20.71	39.90 - 40.45	2.89	2.67	4.34
2025	1.35 - 1.40	5.83 - 5.90	4.73 - 4.78	11.90 - 12.08	4.00 - 4.15	15.72 - 15.92	20.70 - 20.92	40.42 - 40.99	2.96	2.70	4.38
2026	1.37 - 1.42	5.82 - 5.90	4.73 - 4.78	11.92 - 12.10	4.16 - 4.31	15.87 - 16.09	20.91 - 21.13	40.94 - 41.53	3.04	2.73	4.42
2027	1.39 - 1.44	5.82 - 5.90	4.74 - 4.79	11.94 - 12.13	4.32 - 4.48	16.02 - 16.26	21.12 - 21.34	41.47 - 42.08	3.11	2.76	4.46
2028	1.41 - 1.46	5.81 - 5.90	4.74 - 4.79	11.96 - 12.15	4.48 - 4.64	16.18 - 16.43	21.33 - 21.56	42.00 - 42.63	3.18	2.78	4.50
2029	1.43 - 1.48	5.81 - 5.90	4.75 - 4.80	11.98 - 12.18	4.65 - 4.81	16.33 - 16.60	21.55 - 21.77	42.53 - 43.18	3.25	2.81	4.54
2030	1.45 - 1.50	5.80 - 5.90	4.75 - 4.80	12.00 - 12.20	4.82 - 4.99	16.48 - 16.77	21.76 - 21.99	43.06 - 43.74	3.32	2.84	4.58
2031	1.45 - 1.51	5.80 - 5.90	4.74 - 4.80	11.99 - 12.21	4.94 - 5.13	16.64 - 16.94	21.88 - 22.16	43.46 - 44.22	3.40	2.87	4.62
2032	1.46 - 1.52	5.79 - 5.90	4.72 - 4.79	11.97 - 12.21	5.06 - 5.27	16.79 - 17.12	22.00 - 22.32	43.85 - 44.71	3.47	2.90	4.66
2033	1.46 - 1.53	5.79 - 5.91	4.71 - 4.79	11.96 - 12.22	5.18 - 5.41	16.94 - 17.29	22.12 - 22.49	44.24 - 45.19	3.54	2.93	4.70
2034	1.47 - 1.54	5.78 - 5.91	4.69 - 4.78	11.94 - 12.22	5.30 - 5.55	17.10 - 17.47	22.23 - 22.66	44.63 - 45.68	3.61	2.96	4.74
2035	1.47 - 1.55	5.78 - 5.91	4.68 - 4.78	11.93 - 12.23	5.43 - 5.69	17.25 - 17.64	22.35 - 22.83	45.03 - 46.16	3.68	2.99	4.78
2036	1.48 - 1.55	5.77 - 5.91	4.66 - 4.77	11.91 - 12.24	5.55 - 5.84	17.40 - 17.82	22.46 - 22.99	45.42 - 46.65	3.76	3.01	4.82
2037	1.48 - 1.56	5.77 - 5.91	4.65 - 4.77	11.90 - 12.24	5.67 - 5.99	17.56 - 18.00	22.58 - 23.16	45.80 - 47.14	3.83	3.04	4.86
2038	1.49 - 1.57	5.76 - 5.91	4.63 - 4.76	11.88 - 12.25	5.80 - 6.13	17.71 - 18.17	22.69 - 23.32	46.19 - 47.63	3.90	3.07	4.90
2039	1.49 - 1.58	5.76 - 5.92	4.62 - 4.76	11.87 - 12.25	5.92 - 6.28	17.86 - 18.35	22.80 - 23.49	46.58 - 48.12	3.97	3.10	4.94
2040	1.50 - 1.60	5.75 - 5.92	4.60 - 4.75	11.85 - 12.27	6.07 - 6.47	18.00 - 18.53	22.91 - 23.65	46.97 - 48.66	4.04	3.13	4.98
2041	1.51 - 1.61	5.68 - 5.92	4.56 - 4.75	11.75 - 12.28	6.21 - 6.62	17.95 - 18.71	22.88 - 23.82	47.04 - 49.15	4.12	3.16	5.02
2042	1.52 - 1.62	5.61 - 5.93	4.52 - 4.74	11.65 - 12.28	6.36 - 6.78	17.89 - 18.89	22.85 - 23.98	47.10 - 49.65	4.19	3.19	5.06
2043	1.53 - 1.63	5.55 - 5.93	4.47 - 4.74	11.55 - 12.29	6.51 - 6.93	17.84 - 19.07	22.82 - 24.15	47.16 - 50.15	4.26	3.22	5.10
2044	1.54 - 1.64	5.48 - 5.93	4.43 - 4.73	11.45 - 12.30	6.66 - 7.09	17.78 - 19.25	22.78 - 24.31	47.21 - 50.65	4.33	3.25	5.14
2045	1.55 - 1.65	5.41 - 5.93	4.39 - 4.73	11.34 - 12.30	6.81 - 7.25	17.71 - 19.43	22.74 - 24.47	47.26 - 51.15	4.40	3.27	5.18
2046	1.55 - 1.65	5.34 - 5.94	4.35 - 4.72	11.24 - 12.31	6.96 - 7.41	17.64 - 19.61	22.69 - 24.64	47.29 - 51.65	4.48	3.30	5.22
2047	1.56 - 1.66	5.27 - 5.94	4.31 - 4.72	11.14 - 12.32	7.11 - 7.57	17.57 - 19.79	22.65 - 24.80	47.33 - 52.15	4.55	3.33	5.26
2048	1.57 - 1.67	5.20 - 5.94	4.26 - 4.71	11.04 - 12.32	7.27 - 7.73	17.49 - 19.97	22.60 - 24.96	47.35 - 52.66	4.62	3.36	5.30
2049	1.58 - 1.68	5.14 - 5.94	4.22 - 4.71	10.94 - 12.33	7.42 - 7.89	17.41 - 20.15	22.54 - 25.12	47.37 - 53.16	4.69	3.39	5.34
2050	1.60 - 1.70	5.00 - 5.95	4.18 - 4.70	10.78 - 12.35	7.62 - 8.10	17.09 - 20.34	22.49 - 25.28	47.20 - 53.72	4.76	3.42	5.38

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Mechanized Cultivation Increases Labour Efficiency

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ABSTRACT

Farm mechanization facilitates to increase agricultural productivity and improves farm management by replacing human labour. Therefore, mechanical intervention is a vital adaptation strategy for a sustainable rice production system. Thus, this study aims to (i) estimate the amount of mechanical intervention required in rice cultivation, particularly in transplanting and harvesting operation; and (ii) delineate the impact of farm mechanization on rice productivity and employment generation. The primary data were collected through a household survey and key informant interviews. These data were used for projecting rice area, labour requirement, and off-farm employment opportunities in rice cultivation. Besides, secondary data were collected from published literature. The break-even labour requirement per hectare rice cultivation was 2.88 work-days. Labour productivity might be doubled by 2030 subject to bringing 42% and 36% of the total rice area under mechanical transplanting and harvesting, respectively. The projected demands of the transplanter and combine harvester to achieve the goal are 49,172 and 28,382, respectively. The mechanized rice transplanting, weeding, and harvesting reduced labour requirement by 29, 26, and 34%, respectively, compared to the manual operations. Besides, mechanization meets up the demand for labour at a seasonal peak and increases rice productivity. Furthermore, it creates some off-farm (e.g., operating) and non-farm (e.g., manufacturing, repairing, and trading) employment opportunities for operating, maintenance, fabricating, and marketing of the machinery. Syncronize farming is required for enhancing the field efficiency of the farm machine at present size and shape of plots. Besides, the synchronized farming is beneficial for providing service to the farmers at their affordable rental charge. Government assistance should continue and strengthen for the procurement of transplanters and combine harvesters. A holistic approach combining the public and private intervention is essential for achieving the mechanized farming goal for sustainable rice farming in Bangladesh.

Key words: Mechanization, transplanting, harvesting, rice labour, labour efficiency, break-even labour.

INTRODUCTION

Mechanization is the key to modernize agriculture. The government and non-government organizations in Bangladesh have been jointly working for modernizing agriculture through mechanization since early 1980. It is in part because of mechanized cultivation increases the yield and total system productivity through facilitating the early establishment of the following crops by reducing turn around time as well as decreases production cost (Islam, 2020). Mechanized cultivation is an option for sustainable farming using the decreasing labour force. Farm mechanization synonymous with rice farming mechanization in the country as rice covers about 80% of the total crop area, and rice-based cropping pattern is the most extensively practiced cropping system in Bangladesh (Kabir *et al.*, 2015).

Mechanization status

Mechanical intervention in crop production was slowly progressing in the country since the early 1980s. However, the rate of adoption of farm machinery has increased substantially since mid-1990 because of import tax liberalization for two-wheel tractor and small diesel engine, and banning the standardization committee on farm machinery. The government has increased facilities for two-wheel tractor instead of the four-wheel tractor because of its suitability with our environment (e.g., small plots) and socio-economic conditions (e.g., the low purchasing power of farmers). Farm mechanization in the country got momentum after 2009, when the government largely increased subsidies for agricultural mechanization. The combined efforts of different stakeholders, including the ministry, research institutes, extension agents,

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development partners, manufacturers, traders, dealers, and farmers also played an important role in the momentum.

Currently, tillage, irrigation, spraying pesticides, and even the threshing are fully mechanized because of the above-mentioned government and other stakeholders' intervention. However, other labour-intensive major intercultural operations of rice farming like transplanting, fertilizer application, weeding, harvesting, and winnowing are still carried out by humanlabour. The scale of mechanized transplanting and harvesting in the country is extremely low because of the investment in rice transplanter and combine harvester ismuch beyond the purchasing ability of most farm households. Similarly, despite notable post-harvest loss, farmers of the country rely on the sun-drying of rice even in the early wet season and wet season due to scarce access to the mechanical drying facilities (Islam, 2018a). The farm mechanization status of the country is currently atthe development stage and far behind the fully mechanized countries such as Korea and Japan (Islam, 2016). Therefore, researchers and development partners are jointly working for developing an economically sustainable business model for expediting farm mechanization in Bangladesh through disseminating transplanter and combine harvester at farmers' fields by local service providers.

Challenges for farm mechanization

The key challenges of large scale farm mechanization in the country are included (i) the lack of suitable farm machines for the condition of Bangladeshi lands and small size plots, (ii) the low purchasing power of smallholder farmers, (iii) the absence of farm road, quality machines, service center, quality spare parts, replaceable tools, accessories, and skilled operators. Besides, lack of suitable infrastructural facilities for the research, development, manufacturing, and quality control also impeded the farm mechanization process in the country. Moreover, inadequate extension services are also a barrier for the dissemination of farm machinery as farmers are not always aware of the benefit of mechanized cultivation. Finally, lack of availability of rules for producing quality farm equipment, proper design and drawing, standard material, fabrication guidelines, skilled manpower, technical assistance, and credit facility as well as the higher tariff for raw material than machines are the barriers for producing farm machinery in the country.

Farm mechanization policies in Bangladesh

Formulating suitable policies considering the socio-economic and land conditions and a holistic approach are critically important for the sustainability of farm mechanization in a country. Following policies have been undertaken in Bangladesh for expediating farm mechanization.

(i) Department of Agriculture Extension (DAE) has taken a short-term program to provide 70% assistance for *haor* areas and 50% assistance for the other areas on the procurement of transplanter, reaper, and harvester in 2020. The Government of Bangladesh allocated Tk 200 crore budget to DAE to execute the program (MoA, 2020).

(ii) The government provided funds to Bangladesh Rice Research Institute (BRRI) to procures combine harvesters in 2009. BRRI organized some large-scale demonstrations on combine harvester at the farmer's field to motivate farmers for mechanized harvesting and threshing. Similarly, the government provided funds to DAE to influence farmers for purchasing combine harvester at subsidized prices. Initially, traders imported recondition harvester in one-tenth price, invested some money for repairing purposes, and sold to the farmers under the government subsidy programme (Islam, 2018a). The DAE also set some large scale demonstrations and provided training for operating and maintenance of combine harvester. About 1,748 combine harvesters of different makes and models are in operations at the farmer field in Bangladesh (Field survey, 2020). Farmers operated the machine to harvest the rice crops and side by side rented out the machine.

(iii) The government of Bangladesh provided funds to BRRI to procure transplanter for demonstration and training purposes in 2009. BRRI organized a demonstration on rice transplanters at farmer fields. Besides, provided training to the farmers on raising seedlings at trays. DAE also distributed the transplanters to the farmers at the government determined subsidized price. DAE also arranged large-scale demonstrations and residential training programmes on the operation and maintenance of transplanters. Presently, 625 transplanters are in operations in the farmers' field (Field survey, 2020).

(iv) Before 1998, farmers usually threshed the paddy and wheat manually. As the labour price going up as well as labour shortage, it became an issue to thresh crops manually. Farmers had been compelled to thresh their crops in power thresher. Field survey indicated that the smaller version was not profitable and farmers preferred the bigger version to use in rental service. In 2009, the government provided a subsidy to farmers on the purchase of power thresher. Now, more than 90% of paddy and wheat are threshed by power thresher.

Rice vision

In 2015, BRRI prepared and published a policy paper on Rice Vision for Bangladesh: 2050 and beyond. BRRI identified several constraints and possible ways to overcome production barriers. This paper suggested that mechanized cultivation is one of the major interventions to achieve the goal. BRRI has taken initiatives to expand mechanized rice cultivation throughout the country (Kabir *et al*., 2015).

Mechanization road map

The government of Bangladesh formulated the "mechanization road map 2021, 2031, and 2041" in 2016. The road mapset the target of mechanical intervention in crop production (Table 1). The road map also encouraged the development partners to be involved actively in achieving the mechanization goal.

Objectives of the study

The labour shortage is becoming severe in crop production. Reduced availability of human labour due to shifting the off-farm wage workers to non-farm wage works and rising wages of off-farm workers mainly influenced farmers to introduce farm mechanization. The government of Bangladesh has also taken action plans to increase agricultural productivity. Farm mechanization is a vital determinant to increase agricultural productivity. This study aims to (i) estimate the mechanical intervention requirement for transplanting and harvesting operations of rice and (ii) delineate the impact of farm mechanization on rice productivity and employment generation.

Table 1. Short, medium and long-term target of bringing net rice cropped area (%) under mechanical intervention of major intercultural activitiesin Bangladesh.

Activity	2016	Short- term (2021)	Medium-term (2031)	Long-term (2041)
Seeding	3	25	50	80
Transplanting	0.1	20	40	80
Harvesting	2	30	60	80

Source: MoA, 2016

METHODOLOGY

The primary data was collected through a household survey and key informant interviews (KII) which were used for projecting rice area, labour requirement, and off-farm employment opportunities for rice cultivation.

Besides, secondary data was collected from published literature. Table 2 presents the projected area under rice cultivation and rice labour scenario during 2016-2050. The labour scenarios were calculated based on per hectare 5 man-days labour required for raising seedling and transplanting rice by transplanter (operator-1, labour (skilled+unskilled)-2, seedling carrying labour-2) (Islam, 2017) and 4 man-days labour (operator-1, unskilled labour-1, bag carrying -2) require for harvesting by the combine harvester.

RESULTS AND DISCUSSION

Farm power availability

Farm power availability is one of the indicators of measuring the mechanization status of a country. The availability of farm power was estimated based on the energy input per unit area of cultivable land. Figure 1 shows the farm power availability in agriculture from 1960 to 2019. Before 1984, power availability in agricultural operations was very low. From 1960 to 1984, the rate of farm power increase was 1.2%. The rate of farm power availability sharply increased to 10% after 2008 because of the large-scale adoption of farm machinery due to supportive government policy and activities of different stakeholders. The progression on the farm power availability in the farming sector has been continuingand it will be reached at 6.0 kW ha^{-1} in 2050 (Kabir *et al.*, 2020) because of strengthening policy supports through providing subsidies on farm machinery purchase and reducing the tariff on farm machinery import (Islam, 2018b).

Labour scenarios

The lack of availability of labour at transplanting and harvesting period of rice affected productivity and increased production cost as wages gone up at the peak season, consequently rice cultivation becomes less profitable under manual transplanting and harvesting. It was also the case that farmers are forced to delay transplanting and harvesting rice because of the unavailability of off-farm wage workers. It not only decreases rice yield but also sometimes increases post-harvest loss or completely damages Boro rice by heavy rain fall or hill surge. Figure 2 presents the labour demand calendar for rice cultivation both for traditional and mechanical operations. Labour requirements for manual harvesting were higher followed by transplanting operation. The wage rate also rises to a peak in the period of higher labour demand. However, mechanical intervention in transplanting and harvesting operations can minimize the seasonal labour crisis.

Table 2. Rice area, labour availability and labour requirement for rice cultivation under future conditions (2020-2050).

Year	Rice area (M ha)	Availability of rice labour (M)	Labour (ha^{-1})	Labourrequirement (M)	Deficit (M)
2016	5.59*	16.08*	2.88	16.08	0.00
2020	5.50	15.06	2.74	15.83	-0.77
2025	5.39	13.97	2.59	15.51	-1.54
2030	5.28	12.56	2.38	15.21	-2.65
2035	5.18	11.50	2.22	14.90	-3.40
2040	5.08	10.34	2.04	14.61	-4.27
2045	4.98	9.17	1.84	14.32	-5.15
2050	4.88	8.00	1.64	14.03	-6.03

Source: Author's calculation based on Kabir *et al.*, 2015

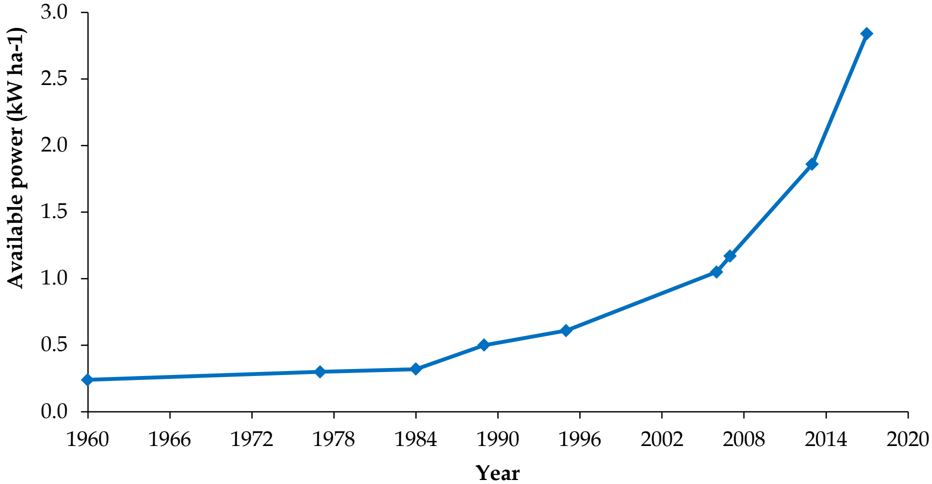

Fig. 1. Farm power availability in the agriculture sector in Bangladesh.
Source: Prepared by the author using the data from Islam, 2010; CSAM, 2015 and Islam, 2018a

Table 4 presents the availability of off-farm labour situation. In Bangladesh, some of the districts are severe and moderate labour shortages in particular at the transplanting and harvesting season of rice. It was because (i) the younger generation prefers non-farm work as a better livelihood option than farming, and (ii) more off-farm labour from the districts shifted to non-farm wage work. The labour shortage districts are dependent on migratory labour from the labour surplus districts for the intercultural operations of rice crops. The districts with less than 25% of agriculture labour households are highly deficient in off-farm wage workers for farming and depend on migrated labour from labour surplus districts for transplanting and harvesting of rice crops (Table 4).

The break-even labour requirement for rice cultivation was 2.88 man-days per hectare. Rice labour decreases due to shifting the labour in the non-farm activities. After 2020, the country might face a severe labour shortage in rice production (Fig. 3). Therefore, mechanization remains as the option to offset the labour shortage in rice cultivation.

Table 3. Human labour requirement for manual and mechanized intercultural activities of rice cultivation.

Technology	Labour requirement		Source
	Manual (man-hr ha^{-1})	Machine, (man-hr ha^{-1})	
Transplanter	123-150	9-11	Islam *et al.*, (2016)
Prilled urea applicator	4	4	Islam *et al.*, (2015b)
USG applicator	4	4	Islam *et al.*, (2015b)
Weeder	86	22	Islam *et al.*, (2017a)
Reaper	80-84	9-10	Alam *et al.*, (2014)
Combine harvester	61	21	Hasan *et al.*, (2019)
Open drum thresher	50-52	20-22	Islam (2006)
Close drum thresher	50-52	14-18	Islam (2006)
Winnower (man-hr t^{-1})	21	5	Ahiduzzaman *et al.*, (2000)

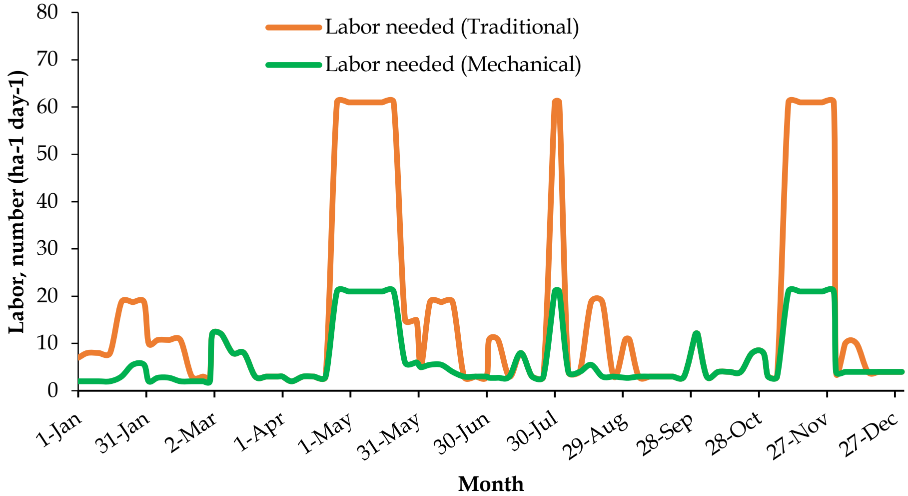

Fig. 2. Labour demand (manual and mechanical) calendar in rice production in Bangladesh.
Source: Author calculation based on field survey 2020.

Table 4. Status of agriculture labour household in Bangladesh.

Farm labour household	District	Status(surplus ordeficits)
Less than 20%	Dhaka, Narayanganj, Chittagong, Gazipur, Narshingdhi, Jhalokhati, Sylhet	Highly deficit districts
21-25%	Feni, Munshiganj, Brahmanbari, Patuakhali	Deficit districts
26-30%	Tangail, Manikganj, Rangamati, Moulovibazar, Cox's Bazar, Barishal, Barguna, Pirojpur, Khulna, Bandarban, Comilla, Chapai Nawabganj	Moderately deficit in some area
31-35%	Bhola, Bogra, Noakhali, Lakshipur, Pabna, Rajbari, Faridpur, Gopalganj, Madaripur, Magura, Kushtia, Narail, Sirajganj, Panchagarh, Khagrachari, Chandpur	Sufficient
36-40%	Rajshahi, Jenaidah, Chuadanga, Sunamganj, Joypurhat, Sariatpur, Kishoreganj, Mymensingh, Habiganj, Rangpur, Nilphamari	Surplus
41% and above	Thakurgaon, Jashore, Netrakona, Jamalpur, Sherpur, Dinajpur, Naogaon, Natore, Lalmonirhat, Gaibandha, Meherpur, Kurigram, Satkhira	Highly Surplus

Source: BBS 2011

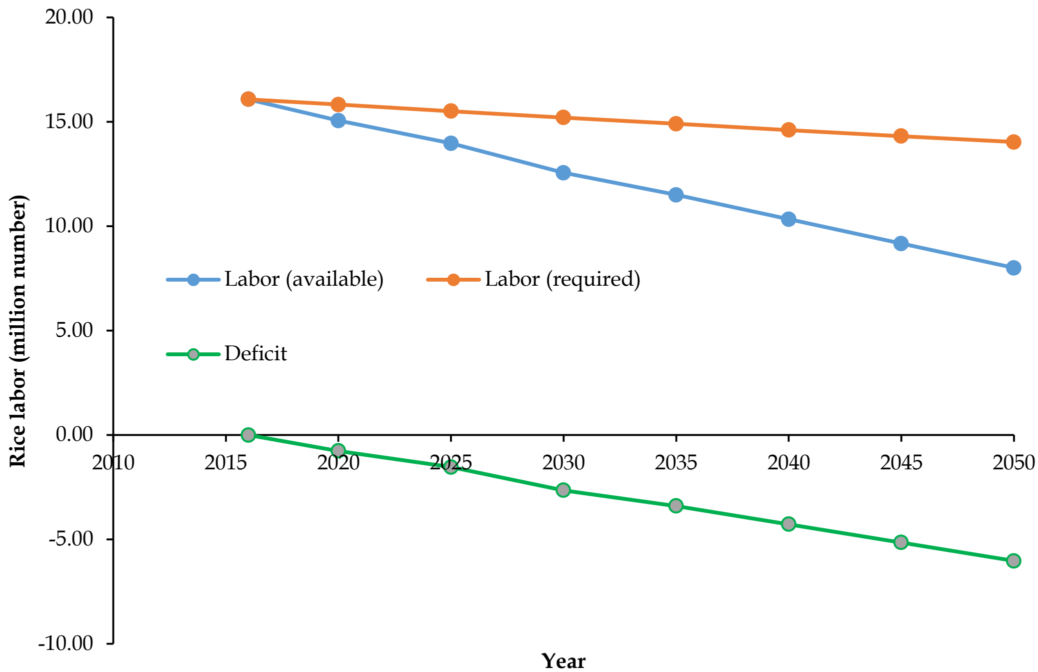

Fig. 3. Projected demand and supply of rice farming labour under future conditions (2016-2050) in Bangladesh.
Note: Analysed and prepared by the author using data from Table 2

Labour efficiency

Table 5 presents comparative statements on the labour efficiency in manual and mechanical means of three major operations of rice cultivation are presented in Table 5. Transplanting by 4-row walking type transplanter, weeding by four-row power weeder and harvesting by mini combine harvester requires, respectively 29, 26, and 34% of the total requirement for manual operation. Therefore, mechanized cultivation of rice is the only solution for increasingly decreasing labour availability for farming in rural Bangladesh. Labour efficiency could be doubled by 2030 if 42% and 36% of the total rice area goes under mechanical transplanting and harvesting, respectively (Tables 6 and 7).

Table 5. Labour efficiency under manual and mechanical operationsin Bangladesh.

Activity	Manual, (md ha^{-1})	Mechanical, (md ha^{-1})	Labourrequirement inmechanical operation (%)	Source
Transplanting	19.00	5.50	29	Islam *et al.*, (2016)
Weeding	10.75	2.75	26	Islam *et al.*, (2017a)
Combine harvester	61.00	21.00	34	Hasan *et al.*, 2019

Note: md ha^{-1} denotes man days per hectare

Table 6. Projected yearly labour requirement (million) at different level of mechanical rice transplanting.

Year	% mechanization									
	35	40	45	50	55	60	65	70	75	80
2016	11.00	10.39	9.77	9.16	8.54	7.93	7.32	6.70	6.09	5.47
2020	10.83	10.22	9.62	9.01	8.41	7.80	7.20	6.59	5.99	5.38
2025	10.61	10.02	9.43	8.83	8.24	7.65	7.06	6.46	5.87	5.28
2030	10.40	9.82	9.24	8.66	8.08	7.50	6.92	6.34	5.75	5.17
2035	10.20	9.63	9.06	8.49	7.92	7.35	6.78	6.21	5.64	5.07
2040	9.99	9.44	8.88	8.32	7.76	7.20	6.64	6.09	5.53	4.97
2045	9.80	9.25	8.70	8.15	7.61	7.06	6.51	5.97	5.42	4.87
2050	9.60	9.06	8.53	7.99	7.46	6.92	6.38	5.85	5.31	4.77

Table 7. Projected yearly labour requirement (million) at different levels of mechanical rice harvesting.

Year	% mechanization									
	35	40	45	50	55	60	65	70	75	80
2016	10.32	9.61	8.89	8.18	7.47	6.76	6.04	5.33	4.62	3.91
2020	10.15	9.45	8.75	8.05	7.35	6.65	5.95	5.25	4.55	3.84
2025	9.95	9.27	8.58	7.89	7.20	6.52	5.83	5.14	4.46	3.77
2030	9.76	9.08	8.41	7.73	7.06	6.39	5.71	5.04	4.37	3.69
2035	9.56	8.90	8.24	7.58	6.92	6.26	5.60	4.94	4.28	3.62
2040	9.37	8.73	8.08	7.43	6.78	6.14	5.49	4.84	4.20	3.55
2045	9.19	8.55	7.92	7.28	6.65	6.02	5.38	4.75	4.11	3.48
2050	9.00	8.38	7.76	7.14	6.52	5.90	5.27	4.65	4.03	3.41

Constrains in farm mechanizations

Land size and shape. The present land ownership system in Bangladesh does not allow the movement of farm machinery from plots to plots. Besides, the land size of the country is mostly small, fragmented, and irregular in shape. The small and fragmented land restricts operating larger size farm machinery. Operational efficiency of the farm machines dependent on the plot size and shape. Therefore, the enlargement of land size is an urgent issue to promote farm mechanization in the country. Similarly it is reported that the small size of the plot decreases the field capacity of the farm machines (Islam, 2018b and Islam *et al*., 2017c). The field capacity of rice transplanters varied based on the size of the plots (Fig. 4).

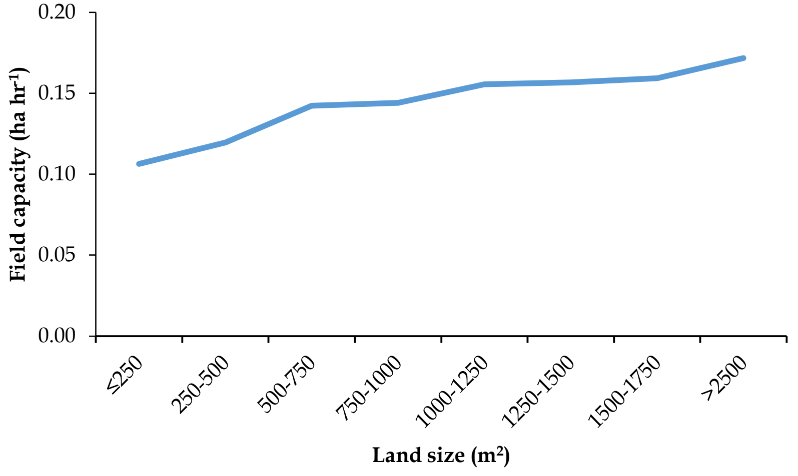

Fig. 4. Field capacity of transplanter with respect to land size.
Note: Graph adopted from Islam, 2018a.

The plot size equal to 1000 m² or higher than that is the potential to achieve the optimum field capacity (e.g., 0.15 ha hr^{-1}) of four-rows walking type transplanter. The field capacity of the transplanter was very low for the plot size below 250 m². Islam *et al.* (2015a) reported that the plot size below 250 m² and 400 m² is not the potential to achieve the minimum level of field capacity of 4-row walking type transplanter and 6-row riding type transplanter, respectively.

The field capacity of the combine harvester continuosly increased with rises plot size due to decreased time waste for taking turns (Fig. 5). The field capacity of 750-1,000 m²plot was 83% higher than the plot size below 500 m². Field capacity of the combine harvester in the plot size below 500 m² unable to achieve minimum economic threshold level. Therefore, the plot below 500 m²is suitable for efficiently operating combine harvester.

Plot length-width ratio. Taniyama (1975) stated that the operation efficiency of farm machinery dependent on the size and the length (L) and width (W) ratio of plots. The ratio of L/W of plots has a notable influence on the performance of farm machinery. The total number of turning events depended on the L/W ratio of the plots and operational path (length or width-wise). The least number of turns were observed for the L/W ratio of 2-2.5 and length-wise transplanting. The number of turning events of the farm machinery will be reduced in length-wise operation and increased in width-wise layout. Length-wise operation of farm machinery is preferable to minimize the turning events. Plot length should be increased by keeping the same plot size (Islam *et al.*, 2017c).

Land fragmentation. Fragmented land increased the plot to plot movement time. Land consolidation of the smaller plots may not be possible at this stage due to the socioeconomic condition of farmers. However, entrepreneurs may follow the operational consolidation by considering plot shape, size, and plot to plot distance while operating the farm machine in the field. Mandal (2017) and Islam *et al.* (2015a) recommended the operational consolidation for increasing the daily area coverage of the farm machine. Careful selection of the plots will reduce the lost time during turning, plot to plot movement, and consequently increase the daily area coverage (Islam *et al.*, 2017c).

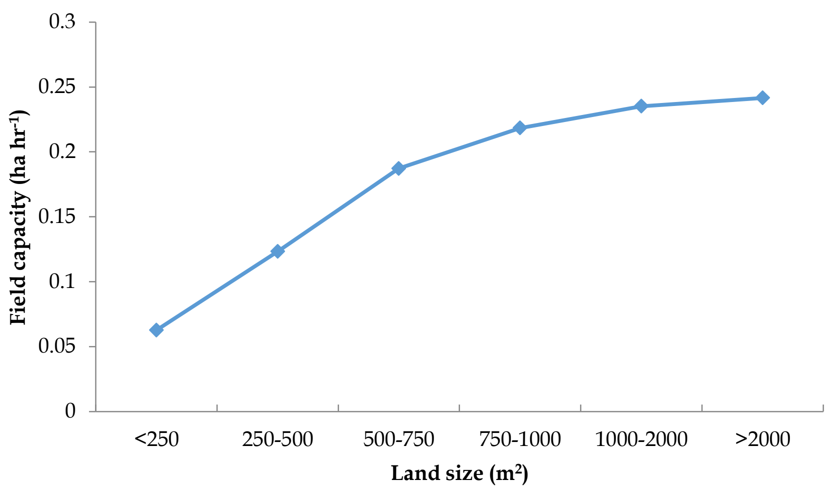

Fig. 5. Field capacity of combine harvester across plot size.
Note: Graph adopted from Islam, 2018a.

Time loss in turning. The total number of turns depends on the plot size and shape. Number of turning decreases with the increase of plot size (Fig. 6a). The size of plots is the determinant of the frequency of turning the requirement of plots. Therefore, the time loss for turning relied on the size of the plots. The time loss for turning decreases with an increase in the plot size (Fig. 6b). The turning time loss was high for the plot size below 500 m^2. It is double for the plot size below 250 m^2compared to plot about 500 m^2. Turning time loss was also dependent on the skills of operators of the machine and the shape of the turning point. The economic threshold level of farm machinery could achieve through enhancing operators' skills and plots size over 500 m^2.

Machinery movement in the field. The operators faced difficulty to move the machine on a sloppy surface as the height of the road from the field surface was observed as more than 2 m. It caused damage to the machine and required extra care. Farm roads should be constructed to access the farm machinery in the land. According to Taniyama (1975), the layout of farm roads should be readjusted to facilitate the movement of farm machines to each field plot without causing damage to machines, levees, and irrigation channels. For Bangladesh, the height of main farm roads and branch farm roads should be 50 cm and 30 cm from the field surface, respectively. Sometimes, farm machinery movement damaged the irrigation channel and levees.

Impact of mechanization on yield

Table 8 presents the yield benefits of mechanized cultivation. It was observed that rice yield increases because of transplanting younger seedlings by transplanters than manual transplanting. Similarly, rice produced a higher rice yield for mechanized weeding and application of urea fertilizer. Likewise, mechanized harvesting by reapers and threshing by power threshers also reduces the grain loss compared to manual harvesting and threshing.

Impact of farm mechanization on employment

Traditionally it would believe that mechanization is not possible in the small and fragmented land and it will create unemployment problems in rural Bangladesh

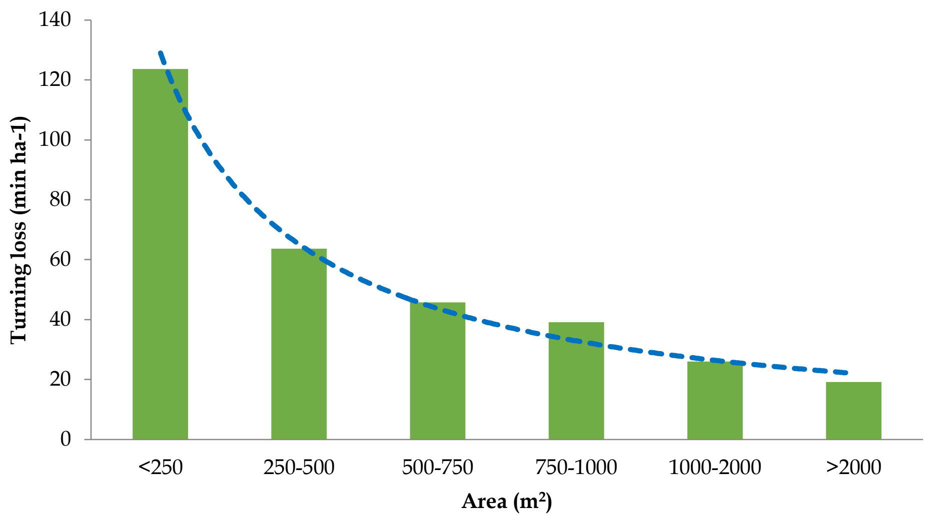

Fig. 6. Time loss for taking turns across plot size.

(Ahmed, 1965; Alim, 1974). However, currently there are some districts in Bangladesh that are highly labour deficit despite fully mechanized tillage and threshing. It is also the case that mechanization creates employment opportunities for off-farm workers as operators. Besides, some people are working for servicing and fabricating the farm machinery. Moreover, some are involved in the business of spare parts and machinery. It indicates that mechanization plays a vital role in creating off and non-farm employment opportunities and improving the livelihood of rural dwellers. Table 9 presents the requirement of skills and unskilled manpower for mechanized transplanting and harvesting of rice in the country from 2016 to 2050.

Entrepreneurial opportunity in farm machinery service business

The development of entrepreneurship on rice transplanters and harvesters has broader scope for self-employment activities (Islam and Kabir, 2017). The private entrepreneurs, including farmers, provide services of farm machinery to the neighboring farmers. Transplanters and combine harvesters are highly investment intensive and require skilled operators to drive the machines. Besides, limited use of the types of machinery during the transplanting and harvesting season of rice is discouraged farmers from investing in those machines only for self-farming. Therefore, developing a business model for custom hire service of the machinery might facilitate to widespread adoption of mechanized transplanting and harvesting in the country. Custom hire services of farm machinery make an enabling environment to provide service to the farmers at the cheapest price (Islam *et al*., 2017b). The objective of the custom hire service is to foster farm mechanization by making easy access to the small and medium holder farmers. It also creates a business venture for the rural unemployed youths. Cash incentives should be provided to encourage entrepreneurs to set up the infrastructure of custom hiring services.

Table 8. Benefit of mechanized rice cultivationin Bangladesh.

Operation	Technology	Yield/output	Source
Transplanting	Transplanter	9-14% yield increase	Islam *et al.*, (2016)
Weeding	Weeder	Increase	Islam *et al.*, (2017a)
Urea fertilizer application	Prilled urea applicator	Increase	Islam *et al.*, (2015b)
	USG applicator	Increase	Islam *et al.*, (2015b)
Harvesting	Reaper	0.26% loss over traditional	Alam *et al.*, (2014)
Threshing	Mechanical thresher	2-3% output increase	Islam (2006)

Table 9. Manpower requirements for mechanized rice cultivation in Bangladesh.

Year	Mechanization (%)	Operator+skilled labour (number)	Mechanic+Attendant (number)
2016	<1	1216	61
2020	15	81,647	4,082
2025	28	148,358	7,418
2030	38	196,687	9,834
2035	56	282,190	14,109
2040	76	375,373	18,769
2045	84	403,898	20,195
2050	90	419,819	20,991

Source: Analysed and prepared by the author using data from field survey 2020 and KII

Power transplanters requirement

The annual area coverage of four-row walking type and eight-row riding type transplanters was estimated considering per annum potentiality of the transplanters are 45 and 80 ha, respectively (Islam and Rahman, 2014). The demand for four/six-row transplanters was projected through accounting that 100%, 98%, and 97% of total rice area would be transplanted by the four-row walking type transplanters and the rest area would be transplanted by the eight-row rice transplanter, respectively by 2020, 2025 and 2030. The projected requirement of rice transplanters for 100% mechanical transplanting is 20,412, 37,090 and 49,172 for 2020, 2025, and 2030, respectively (Fig. 6).

Combine harvester requirement

The demand for combine harvesters was projected considering the annual harvesting capacity of a combine harvester is 70 ha (Islam, 2018a). The projected demand of the combine harvesters for mechanical harvesting of rice cropping area in Bangladesh is 11,662, 21,336, and 28,382 in 2020, 2025, and 2030, respectively (Fig. 7).

Intervention required for mechanized farming

Policy supports for disseminating power transplanters. Islam (2016) stated that the purchase price of the transplanter in Bangladesh is higher than that in Korea whereas labour price is the cheapest (12 times lower) in Bangladesh compared to Korea. On the other hand, the cost of manual transplanting is 7.5 times higher in Korea than in Bangladesh. In Bangladesh, farmers have to sell 18 tons of paddy to buy a transplanter whereas, in Korea, farmers can buy the same transplanter by selling 2.5 tons of paddy. Therefore, investment in mechanized transplanting is beyond the investment ability of most farmers, so that it requires government support to make the transplanting venture viable (Islam, 2016). In 1981, the Korean government provided 50% subsidy, 40%loan, leaving farmers' own expense at ten percent (with an eight percent annual interest rate) to the organizations since 1986 to procure agricultural machinery to minimize the burden of the farmers. The loan repayment period of small farmers extended to seven years with a three-year grace period, and the interest rate decreased to 3%. The repayment period of the credit, with which a farm household borrowed to purchase farm machines, was also extended to seven years with a five-year grace period (AMK, 2000). Bangladesh can follow the Korean mechanization policy considering the socio-economic conditions of the farmers. Islam (2016) also mentioned that cash incentives dependent on the annual area coverage by a transplanter. For a profitable custom hire service of transplanting,about 80% of the total price of a power transplanter needs to provide as a subsidyfor procuring a transplanter if a transplanter can transplant rice in the 15 ha area. However, the requirement of the subsidy decreased to 60% with an arrangement of 30% soft loan of the total price of the transplanters if the capacity increased to 25 ha.

Policy supports for disseminating combine harvesters. The government of Bangladesh has taken an action plan to promote mechanized harvesting in the country. The government provided 70% assistance for the haor areas and 50% assistance for the other areas on the procurement of harvester in 2020. Field survey indicated that bigger size of the combine harvester is more business viable than small size. However, the price of bigger sizes combine harvester is beyond the purchasing power of the entrepreneurs. Due to the limited annual use and price of the machine, the incentive should be increased to 70% for all the areas, 20% soft loan, and the remainder of the ten percent farmer's expenses to create the

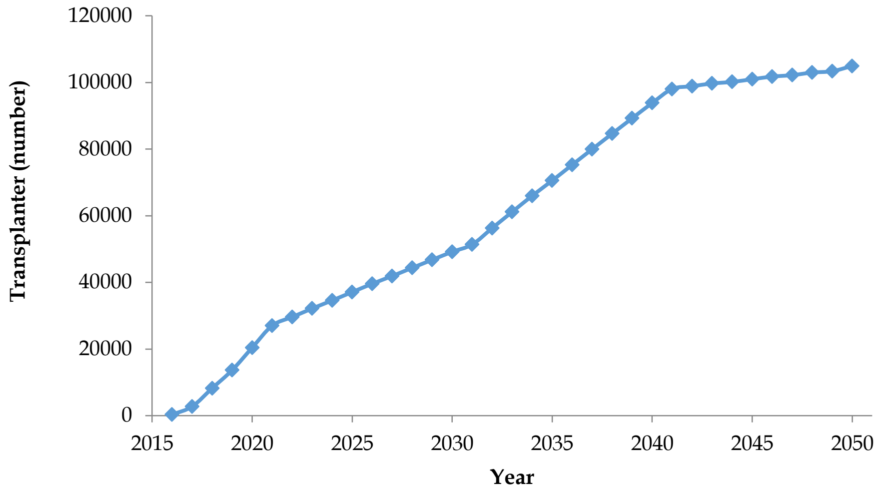

Fig. 6. Demand of rice transplanters for fully mechanized transplanting under future condition (2016-2050) in Bangladesh. Source: Analysed and prepared by the author using data from field survey 2020

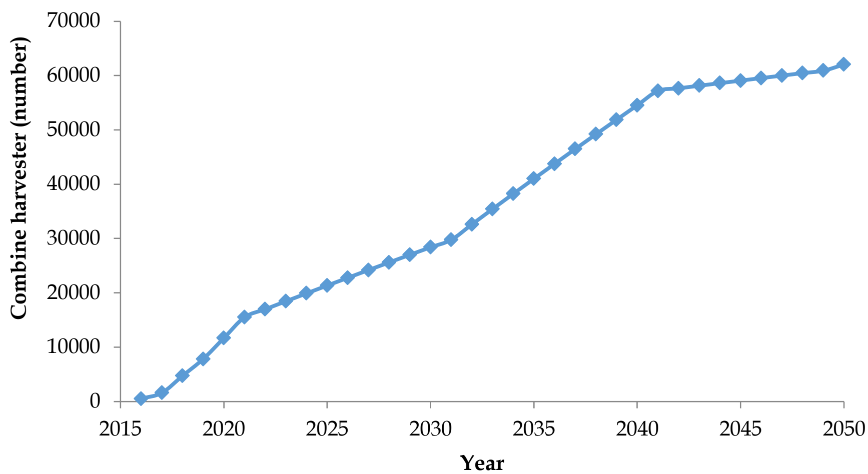

Fig. 7. Demand of combine harvester for mechanized rice harvesting under future conditions (2016-2050) in Bangladesh. Source: Analysed and prepared by the author using data from field survey 2020.

harvesting business more viable. The entrepreneurs will contract with the farmers willing to harvest their rice crop by combine harvester and prepare harvesting schedule based on the position of the plots to provide the service to them.

Business model for disseminating transplanter. A subsidy for procuring transplanters should provide as above mentioned rate to service providers or entrepreneurs to provide the services to the farmers at an affordable rental charge. Farmers have to use the quality seed for raising rice seedlingsin the trays at their premises. The seedling management on the trays is as like as they would traditionally practice for raising seedlings in the nursery. Local service providers or entrepreneurs will provide custom hire services of mechanical transplanting of rice using farmers' raising seedlings at trays.

Business strategies. Farm machinery entrepreneurs can move to another area after completing work in one area in a short time. This will enable them to run service business of farm machinery profitably and will play a helpful role in creating a business-friendly environment.

Synchronize cultivation

Synchronized cultivation is meant to transplant the variety having the same growth duration at the same time in certain areas to facilitate the transplanting and harvesting crops by machine. This will make the transplanting and harvesting business profitable and reduce the production cost of the farmer. Synchronize cultivation should be done within the command area of a deep tube well to ensure irrigation water supply as well.Larger size of the land is preferable to operate the farm machinery at full capacity. However, daily area coverage of farm machinery can be increased in small size of plot through cultivating variety having similar growth duration in the adjacent plots. Different varieties of the same crop with the same growth duration can also be cultivated. Then threshing drum should be cleaned thoroughly to avoid seed mixing while harvesting with a combine harvester. It is better to cultivate the same variety in the same area to avoid seed mixing. Besides, raising seedling in the trays enhance capacity of the transplanters. Seed germination should be above 95% to avoid missing hill. Seeds need to be purified before incubation. Not all seedlings can be raised on the same day in the trays. Seedlings need to be prepared in different steps within a week. Sprouted seeds should be sprinkled evenly in the trays, so that there is no gap in the fields. Uneven distribution of seed created patchy seedlings and ultimately increase the missing in the field. After sowing the seeds evenly, one layer of soil should be lightly applied. The top layer of soil should not be too thick. Manual transplanting should also follow the rows for easier inter-cultural operations and operating combine harvesters. The fields located in the far should transplant earlier to reduce the time loss. However, the harvesting should commence from the adjacent plots. In order to expedite and popularize farm mechanization at the field level, under the supervision of the Ministry of Agriculture, Department of Agriculture Extension in association with BRRI experimentally started to synchronize cultivation in 20 acres of land in some selected blocks in each of the 12 districts of the country in the Boro 2019-20 (Field survey, 2020).

BRRI may provide facilitate synchronized farming through supporting to select rice variety and farm machinery, recommend fertilizer dose, giving advisory services on diseases and insect control methods, increasing cropping intensity i.e., productivity, monitoring farming activities around the crop period and the creation of entrepreneurs.

The synchronized cultivation is the potential to reduce time loss for moving farm machinery from one plot to another. Besides, the operating area of farm machinery will increase ormore land will be transplanted and harvested in a day because of synchronized cultivation. Moreover, water management and weeding will be carried out efficiently under synchronize cultivation. Furthermore, disease and insect pests infestation will be less and pest controlwill be easier. Therefore, mechanized cultivation will be profitable even in the small plots under synchronized cultivation (Fig. 8).

Transplanting Harvesting

Fig. 8. Transplanting and harvesting in synchronize plot.

Development of skilled operators. Trained and skilled drivers are essential for efficiently operating the farm machinery. The operators must know the strategy of transplanting seedlings in the headland. The operators should know the approach of driving the machine efficiently in the plots surrounded by crops on its two or three sides. Transplanting and harvesting machine should operate at walking speed. Sudden turns should be avoided to prevent accident.

Implementation strategy

The goal of fully mechanize farming may not be feasible to achieve by only government intervention. It requires combined interventions including the public (e.g., ministry, research and extension), private stakeholders (traders, manufacturers and mass media), and development partners. The policy supports are needed for achieving the following strategies:

- Cash subsidies to service providers or entrepreneurs, including farmers to purchase transplanters, reapers, and combine harvesters should continue and strengthen.
- BRRI may provide hands-on training to the agricultural engineers, sub-assistant agricultural officers, farmers, and operators on tray preparation techniques, operation, repair, maintenance, and supervision of farm machinery.
- The capacity of DAE should strengthen through establishing an agricultural engineering wing for rapid dissemination of the farm machinery and associated technology as well as to provide training for developing skilled manpower for operating and maintenance of the farm machines.
- The government cash supports should strengthen for developing entrepreneurship for hiring out farm machinery at custom hire basis, marketing farm machinery, and workshop for fabricating machines.
- The business model for the different types of farm machinery should develop to run the service business profitably.
- Extension service should be strengthening for mechanical transplanting in a location using the rice variety having similar growth duration (i.e., called synchronize farming) to facilitate mechanical harvesting the rice at a time for creating a business opportunity for rental service providers.

Action plan

An action plan has been prepared with ten years interval to achieve the target of mechanized cultivation in 2030 and beyond (Table 10).

Table 10. Action plan of mechanized cultivation.

Theme	2021-2030						2031-2040						2041-2050					
	A	DD	T	V	D	Tr	A	DD	T	V	D	Tr	A	DD	T	V	D	Tr
Suitability test of the imported mechanical transplanter and harvester	■						■											
Selection of design criteria based on our land tenure system, crop nature, climate and socio-economic condition of the farmer		■																
Design and development of transplanter and harvester based on the test results		■					■	■	■									
Research and development of farm machinery through public-private partnership		■					■					■			■			
Strengthening research capacity of the researcher, and farm machinery manufacturer	■					■	■					■	■					■
Risk analysis of the local farm machinery manufacturing industry	■																	
Occupation hazard analysis of the local farm machinery manufacturing industry	■																	
Test the business viability of the farm machinery	■	■	■	■	■						■				■			
Development of business model of the farm machinery service	■	■	■	■	■					■	■							
Entrepreneurship development on the farm machinery manufacturing and service	■	■			■					■	■					■		
Assessment of training needs of the researcher, workshop personnel, manufacturer, progressive farmers, operator, mechanic and entrepreneur	■																	
Assessment of present land size, shape and farm road	■								■									
Precision agriculture	■						■	■	■					■	■	■	■	■
Remote sensing	■						■	■	■					■	■	■	■	■

A = Assessment T = Testing D = Dissemination

DD = Design and development V = Validation Tr = Training

CONCLUSION

Labour efficiency might double by 2030 subject to bring 42% and 36% of total rice area under mechanical transplanting and harvesting, respectively. The large-scale dissemination of mechanical transplanting and harvesting will be facilitated to transplant rice within the optimum planting period and harvest the rice crops without delay. As a result, the unexpected yield loss of stape food crops due to delay transplanting and harvesting due to the unavailability of labour will be reduced substantially. Synchronize rice farming is essential to optimize the field efficiency of the farm machine under the present size and shape of the plots. Besides, synchronize farming is beneficial for providing service to the farmers at their affordable rental charge. Government supports for the procurement of transplanters and combine harvesters should continue and further strengthen.

RECOMMENDATION

- Sufficient funds should be allocated to promote the mechanized farming.
- Strengthening local farm machinery manufacturing industries.
- Hands-on training should be arranged to develop skilled operator and mechanic.

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DECLARATION OF INTERESTS

A version of the paper was published in a book "Doubling Rice Productivity in Bangladesh" in 2020 by the Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh to commemorate BRRI's 50th anniversary. The Bangladesh Rice Journal has prior knowledge of the book publication and does not see any conflict of interest.

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Increasing Rice Yield through Targeting Genetic Potentials by Rice Types

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ABSTRACT

Bangladesh needs an average rough rice yield of 9.11 t ha^{-1} by 2050 which can not be achieved equally across all the geographic regions since the country has various 'rice types' with varying yield potentials. This paper focuses on strategic innovations for reaching the yield target by refining rice types. Based on rice ecosystems and the pressing needs, we divided rice areas of Bangladesh in 17 different types. We estimated year-wise land areas and allocated achievable yield targets for each of the rice types. Finally, we compared the target yields and the yields of top-yielding rice varieties in Bangladesh by 2020 across the rice types to understand the current status of our varietal improvement programmes. We sorted out how much improvement is needed in each rice types. Among the rice types, cold-tolerant (Northern and Western) was sorted out as the most potential area of rice yield improvement where rice varieties will be released having a yield advantage of 4.04 t ha^{-1} by 2050. The chronology of next priority areas for high yielding variety development and their target yield advantages in t ha^{-1} are saline Boro (4.03), Favourable Boro (long duration) (4), cold-tolerant (Haor) (3.83), tidal submergence (3.8), Healthier rice (Boro) (3.58), Favourable Boro (short duration) (3.33), Healthier rice (Aman) (3.3), Favourable Aman (3.23), Flash flood (3.09), upland rice (2.89), Saline Aman (2.8), Healthier rice (Aus) (2.53), Premium quality rice (2.53), drought (2.38), T. Aus (2.05) and deepwater. Combined genetic interventions like population improvement through cyclic breeding, genomic selection, marker-assisted selection, genome editing, genetic transformation, germplasm utilization through genome-wide association study and phenomics, and development of super hybrid rice are being used in the country to attain yield target for different rice types.

Key words: Rice types, plant breeding, biotechnology, germplasm, hybrid rice.

INTRODUCTION

Rice production in Bangladesh has been phenomenal in the last 45 years; the country is now producing surplus rice (Kabir *et al.*, 2015). However, more rice will be required to produce in the years to come to feed the increasing population. An estimate says 44.6 MT of clean rice will be required in 2050 (Kabir *et al.*, 2015) compared with 35.3 MT that has been produced in 2015 (Kabir *et al.*, 2015). Unfortunately, this possesses a great challenge to meet the future demand for rice domestically.

Rice areas in Bangladesh, standing at 11.28 Mha in 2015 and will be 11.87, 12.10, 12.04, and 11.07 Mha respectively, in 2020, 2030, 2040, and 2050 (Kabir *et al.*, 2020). Improving continued genetic potential through increasing yield would be the base for meeting the country's rice demand.

Accordingly, a minimum of an average rough rice yield target of 9.11 t ha^{-1} has been set for 2050 (Kabir *et al.*, 2015). However, this target can not be achieved equally across all the geographic regions of Bangladesh. Because, the country has various 'rice types' based on specific ecosystems, and also due to the pressing 'needs'. All these 'rice types' have different situation-specific yield potentials and area coverages.

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With the above background, this article undertook three specific objectives in relation to achieving the future target genetic yield potential (GYP) in Bangladesh: (i) presentation of the changing status of target GYP over the decades, (ii) highlighting the scenarios of challenges achieving target GYP across rice types, and (iii) development and mapping the action plans for three decades on achieving target GYP by genetic interventions being carried out by the Bangladesh Rice Research Institute (BRRI). It may be noted that BRRI is the prime institute for rice research in the country and BRRI released 106 inbred and hybrid rice varieties. Additionally, this paper incorporates ongoing and future actions of rice breeding, biotechnology, hybrid breeding and germplasm interventions of BRRI toward achieving GYP of rice in Bangladesh.

MATERIALS AND METHODS

We define the following rice types of Bangladesh based on ecological adaptation, and/or product need to better estimate the changing status of target GYP over the decades.

Rice types

Favourable Boro (Short duration). We define Favourable Boro (short duration) rice cultivars grown in the Boro season (dry season) in Favourable environments (no potential abiotic stress excluding natural calamities) having a life span within 145 days.

Favourable Boro (Long duration). Favourable Boro (Long duration) rice type covers rice cultivars of favourable Boro environments (no potential abiotic stress excluding natural calamities) but the life duration of such cultivars is more than 145 days.

Saline (Boro). Saline (Boro) rice cultivars are cultivated in the saline prone coastal part of Bangladesh in the Boro season.

Cold tolerant (Haor). A haor in the north-eastern part of Bangladesh, physically is a bowl-shaped shallow depression. It receives surface run-off water during monsoon and becomes vast stretches of turbulent water for several months. This vast stretch becomes suitable for rice cultivation in the Boro season for a short period. Short-duration Boro rice varieties having cold tolerance both at vegetative (active tillering stage) and the reproductive phases (pollen mother cell division stage) are ideal for this region.

Cold tolerant (Northern and western). Rice varieties with cold tolerance at the vegetative phase (seedling and active tillering stage) are suitable for Boro cultivation in the northern and western regions of Bangladesh.

Healthier rice (Boro). After getting food sufficiency, Bangladesh is now moving towards producing quality food. As a part of this effort, BRRI is releasing rice varieties rich in micronutrients like iron, zinc, etc. We name thesemicronutrient and vitamin-rich rice varieties cultivated in the Boro season as healthier rice (Boro).

Favourable Aman. Favourable Aman (FA) is the rain-fed Aman rice ecosystem seemingly having no adverse climatic and soil conditions. This type of rice has a maximum acreage in Bangladesh.

Saline (Aman). Saline (Aman) rice is cultivated in the coastal belt of Bangladesh during Aman season.

Flash flood. The northern regions of Bangladesh often experience a flash flood in the monsoon requiring rice varieties having submergence tolerance for 2-3 weeks during the vegetative phase. Rice varieties having this property fall under flash flood rice.

Drought. The north-western part of Bangladesh is drought-prone and rain-fed rice in those areas face terminal drought frequently. Therefore, drought-tolerant Aman rice cultivars are preferably grown in those areas which are regarded as drought rice.

Tidal submergence. The tidal submergence ecosystem lies in the southern region which is tidal prone and one of the major unFavourable ecosystems of Bangladesh. This ecosystem includes both saline and non-saline conditions. Mostly T. Aman rice is grown in the non-saline areas. Rice with taller seedling height can survive under tidal submergence and hence rice varieties with similar traits are categorized under this type.

Deepwater. Medium-level elongation capacity and lodging tolerance are crucial for surviving in the unfavourable semi-deepwater areas of Manikganj, Cumilla, and Faridpur. Rice cultivars grown in these areas are deepwater rice.

Healthier rice (Aman). We name micronutrient and vitamin-rich rice varieties cultivated in Aman season as healthier rice (Aman).

Upland. Upland rice is also a short-duration (March to July) rainfed ecosystem where seeds are broadcasted in the main rice fields.

T-Aus. T-Aus is a partially rain-fed short-duration rice (April to August) where seedlings are transplanted in main rice fields.

Healthier rice (Aus). We name micronutrient and vitamin-rich rice varieties cultivated in the Aus season as healthier rice (Aus).

Premium quality rice. Grain aroma, fine texture, and tastiness provide premium prices in the rice market home and abroad. Therefore, rice with such attributes falls under premium quality rice (PQR).

In order to estimate changing status of target GYP over the decades, first we had to estimate the changing land allocation for rice types over the decades.

Changing status of land allocations for rice types over the decades

The total rice cultivated areas of 2015 (BBS, 2018) and the projected year-wise rice land (Kabir *et al.*, 2020) data were taken as baseline. We got different ecosystem areas (Pandey and Bhandari, 2018) and stress-prone arable land areas in Bangladesh (Iftekharuddaula *et al.*, 2011; Karim *et al.*, 1990). However, none of the data sources could combine the complete rice ecosystems of Bangladesh. Also, we needed to allocate lands for quality rice and nutrient-rich rice. Altogether we partitioned the total rice cultivated areas into 17 different rice types. We needed to split the land areas for different rice ecosystems into the 17 rice types logically.

Changing status of target GYP over the decades

National paddy yield targets for rice types over different years were determined based on the required yield increment rate. Potential yields for 2015 of rice types were used as base yields. The base yields of 2015 of rice types were assumed considering mainly potential yields of available varieties of those rice types areas. We considered a national annual rice yield increase of 1.39, 1.36, 1.24, and 1.30 percent from 2015 to 2020, 2021 to 2030, 2031 to 2040 and 2041 to 2050 respectively (Kabir *et al.*, 2020).

Challenges achieving target GYP across rice types

To determine rice types having bigger challenges, firstly we relied on the best existing varieties for rice types by 2020. Then we compared their yields with the target yields in 2050 for the respective rice types. We calculated the difference between the target yields of rice varieties in 2050 with the highest potential yields of rice varieties so far released by 2020 according to rice types. When a rice type had suitable varieties both under inbred and hybrid categories, we assumed 80% adaptation for an inbred variety and 20% adaptation for a hybrid for potential yield calculation of that rice type. Then, we ranked the priority rice improvement areas based on the magnitude of the differences between the target yield by 2050 and the highest potential yields of rice varieties by 2020.

Development and mapping the action plans for three decades on achieving target GYP

To achieve the set GYP targets for 17 rice types in the three decades through to 2050, this paper has mapped an action plan accounting for ongoing and potential tools on rice breeding, biotechnology, hybrid breeding, and germplasm enhancement. The action plan includes research and development in respective fields, which were worked out through expert consultation.

RESULTS AND DISCUSSION

Changing status of land allocations for rice types over the decades

The total cultivated rice areas in 2015 were 11.28 Mha. Our projected rice land will be 11.87, 12.10, 12.04, and 11.07 Mha respectively, in 2020, 2030, 2040, and 2050 (Kabir *et al.*, 2020). Rice area acreage for FA is the largest and will remain so over the years. On the contrary healthier rice (Aus) covers minimal coverage (Table 1).

Table 1. Area coverage of rice types (Mha) in Bangladesh during 2015-2050.

Rice type	2015	2020	2030	2040	2050
Favourable Boro (short duration)	1.06	1.09	1.06	1.00	0.87
Favourable Boro (Long duration)	1.16	1.19	1.16	1.10	0.96
Saline Boro	0.59	0.61	0.59	0.57	0.49
Cold tolerant (Haor)	0.59	0.61	0.59	0.57	0.49
Cold tolerant (Northern and Western)	0.40	0.41	0.40	0.38	0.33
Healthier rice (Boro)	0.20	0.20	0.21	0.19	0.17
Favourable Aman	2.32	2.49	2.64	2.74	2.62
Saline Aman	0.72	0.77	0.82	0.85	0.81
Flash flood	0.72	0.77	0.82	0.85	0.81
Drought	0.72	0.77	0.82	0.85	0.81
Tidal submergence	0.52	0.56	0.59	0.61	0.59
Deepwater	0.52	0.56	0.59	0.61	0.59
Healthier rice (Aman)	0.22	0.24	0.25	0.26	0.25
Upland rice	0.29	0.29	0.29	0.27	0.24
T. Aus	0.77	0.80	0.78	0.73	0.64
Healthier rice (Aus)	0.08	0.09	0.08	0.07	0.07
Premium quality rice	0.40	0.41	0.40	0.38	0.33
Total land	11.28	11.87	12.10	12.04	11.07

Changing status of target GYP over the decades

The base yield of Favourable Boro (long duration) rice in 2015 was assumed maximum and yield targets over the years will remain maximum following the year-wise required increment rate. On the other hand, base yield and projected yield targets are the lowest in deepwater rice since the base yield of deepwater rice in 2015 was minimum among the rice types (Table 2).

Challenges achieving target GYP across rice types

We have a major challenge in cold-tolerant (Northern and western) rice type since our target is to reach the yield of 10.04 t ha^{-1} by 2050 in this rice type and to date, we have the highest yielder, BR18 with a potential yield of 6 t ha^{-1} (Table 3) lagging behind 4.04 tha^{-1} from the target (Fig. 1). The chronology of next priority areas for high yielding variety development and their target yield advantages in t ha^{-1} are Saline Boro (4.03), Favourable Boro (long duration) (4.00), Cold-tolerant (Haor) (3.83), Tidal submergence (3.80), Healthier rice (Boro) (3.58), Favourable Boro (short duration) (3.33), Healthier rice (Aman) (3.30), Favourable Aman (3.23), Flash flood (3.09), Upland rice (2.89), Saline Aman (2.80), Healthier rice (Aus) (2.53), Premium quality rice (2.53), Drought (2.38), T.Aus (2.05) and deepwater. We already have surpassed the target in deepwater rice by 1.22 t ha^{-1} due to the development of BRRI dhan91 (Fig. 1).

Table 2. Potential rough rice yield (tha^{-1}) of different rice types during 2015-2050.

Rice types	2015	2020	2030	2040	2050
Favourable Boro (short duration)	6.69	7.16	8.13	9.14	10.33
Favourable Boro (Long duration)	7.81	8.60	9.77	10.99	12.42
Saline Boro	6.69	7.16	8.13	9.14	10.33
Cold tolerant (Haor)	6.69	7.16	8.13	9.14	10.33
Cold tolerant (Northern and Western)	6.50	6.95	7.90	8.88	10.04
Healthier rice (Boro)	6.91	7.39	8.40	9.45	10.68
Favourable Aman	6.30	6.74	7.66	8.61	9.73
Saline Aman	5.70	6.10	6.93	7.79	8.80
Flash flood	5.24	5.61	6.37	7.16	8.09
Drought	5.10	5.45	6.20	6.97	7.88
Tidal submergence	6.02	6.44	7.32	8.23	9.30
Deepwater	1.80	1.92	2.19	2.46	2.78
Healthier rice (Aman)	6.02	6.44	7.32	8.23	9.30
Upland rice	4.46	4.77	5.42	6.10	6.89
T.Aus	5.02	5.37	6.10	6.86	7.75
Healthier rice (Aus)	3.90	4.17	4.74	5.33	6.03
Premium quality rice	3.90	4.17	4.74	5.33	6.03
Weighted average yield	5.90	6.31	7.17	8.06	9.11
National annual rice yield increase (%)	-	1.39	1.36	1.24	1.30

Table 3. Rice yield target by 2050 versus progress made in Bangladesh by 2020 in rice types.

Rice type	Highest yielding varieties by 2020	Potential yield (t ha^{-1})	Target in 2050 (t ha^{-1})
Favourable Boro (short duration)	BRRI dhan81, BRRI dhan84, BRRI dhan86, BRRI dhan88, BRRI dhan96, BRRI hybrid dhan3, BRRI hybrid dhan5	7.00	10.33
Favourable Boro (Long duration)	BRRI dhan89, BRRI dhan92	8.42	12.42
Saline Boro	BRRI dhan 67	6.30	10.33
Cold tolerant (Haor)	BRRI dhan45	6.50	10.33
Cold tolerant (Northern and Western)	BR18	6.00	10.04
Healthier rice (Boro)	BRRI dhan74	7.10	10.68
Favourable Aman	BRRI dhan87, BRRI hybrid dhan6	6.50	9.73
Saline Aman	BRRI dhan54	6.00	8.80
Flash flood	BRRI dhan52	5.00	8.09
Drought	BRRI dhan71	5.50	7.88
Tidal submergence	BRRI dhan44, BRRI dhan76	5.50	9.30
Deepwater	BRRI dhan91	4.00	2.78
Healthier rice (Aman)	BRRI dhan72	6.00	9.30
Upland rice	BRRI dhan83	4.00	6.89
T.Aus	BRRI dhan 48, BRRI hybrid dhan7	5.70	7.75
Healthier rice (Aus)	BRRI dhan43	3.50	6.03
Premium quality rice	BRRI dhan34	3.50	6.03

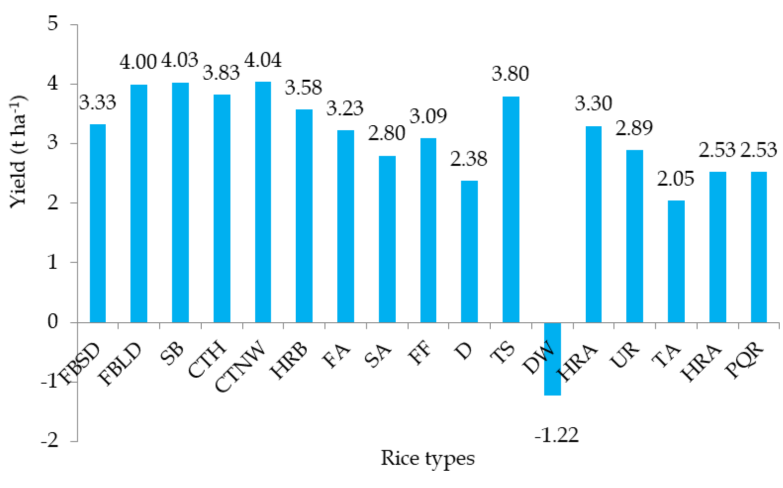

Fig. 1. Required yield improvement in rice types to meet the target by 2050.

Note: FBSD: Favourable Boro (Short Duration), FBLD: Favourable Boro (Long Duration), SB: Saline Boro, CTH: Cold-Tolerant (Haor), CTNW: Cold-Tolerant (Northern and Western), HRB: Healthier Rice (Boro), FA: Favourable Aman, SA: Saline Aman, FF: Flash Flood, D: Drought, TS: Tidal Submergence, DW: Deepwater, HRA: Healthier Rice (Aman), UR: Upland Rice, TA: T.Aus, HRA: Healthier Rice (Aus), PQR: Premium Quality Rice.

Development and mapping the action plans for three decades on achieving target GYP

Interventions for germplasm enhancement leading to increase the productivity

Rice genetic resources are the most basic raw materials for the varietal improvement programs. A wider genetic base is very crucial for any improvement including production. This diversity comprises native landraces, local selections, elite/exotic cultivars, and wild relatives. The role of germplasm in the improvement of cultivated plants has been well recognized. A collection has little practical use if it has not been properly characterized/ evaluated and its attributes become known to breeders. Characterization includes receiving new samples, increasing these seeds, characterization and preliminary evaluation, and also more detailed evaluation and finally documentation.

BRRI Genebank has short, mid, and long-term storage facilities and the germplasm may be preserved safely for 50 to 100 years. Until now, 8604 germplasm have been registered and conserved in the Genebank, where around 5300 local landraces, 1400 pure lines, 1600 exotic *indica*, 100 *japonica,* and 46 wild species are available for utilization. Moreover, 90 wild rice samples were conserved in *ex-situ* type field conservation at BRRI net house.

Till 2018, a total of 907 germplasm were found moderate to highly resistant to different diseases and pests. Among those, 108 for blast, 76 for sheath blight, nine for stem rot, 638 for bacterial blight, one for bacterial leaf streak, two for bakanae, 13 rice tungro, and 52 for ufra diseases; 16 for BPH, 14 for GLH, 33 for WBPH, five for rice gall midge and seven for stem borer insects and 110 found tolerant against abiotic factors like submergence (20), tidal submergence (2), salinity (54), waterlogged condition (2), heat (15), cold (6) and drought (11). Besides 23 were found with long slender quality, 42 with a higher protein, 71 having anaerobic stress tolerant, three for good popping quality and 27 showed moderately allelopathic reaction (Table 4). Traditional rice varieties also possess outstanding characteristics such as aroma, grain and good cooking qualities, and tolerance to drought, flood, cold, salinity, and submergence. It is worth mentioning here that HabiganjBoro II, Hashikalmi, and Dular have a protein content of about 12% (Khalequzzaman *et al*., 2012; Nasiruddin and Bashar 1985).

Table 4. List of germplasm showing resistance/tolerance to different biotic, abiotic stresses and nutritional properties which may be used for doubling productivity (BRRI Annual reports of 1970-2018).

Parameter	Germplasm
Blast resistance	Dular, Kataktara, DNJ-60, BR3, BR4, BR5, BR6, BR8, BR12, BR16, BR18, BR20, BR26, Shamraj, Malshira (2) and Betu. Sixteen aromatic germplasm provided the lowest mean cluster disease score against blast and also confirmed using molecular marker.
Sheath blight resistance (Moderate)	Kataktara, Charnock, Sada pankaich, Katiksail, Chilknal, Gogragoira, Kalamanik, Hasa, Saria saita, Kajalsail, Mogail balam, Absaya, Muktahar, Fulkaiz, Kalagura, Norio, Asmaita, Halud Jaron, Arali, Hashful, Koia, Chinigura. Chotamona, Kuchi, Jotabashful, Kalamona, Kumragoir, Lohagor, Lotamona, Dudhkalam, Kalajira, Kurchi magi, Arman sardar, Dudbazal and Murali. Forty genotypes were found tolerant under supplemental irrigation conditions.
Stem rot resistance	Beto, Ghigoj, Kataribhog, Mala J-15, Hashikalmi, Dular, Dharial, BR3 (tall) and BR9.
Bacterial blight resistance	Gabura, Khama, DV 85, Dhalikhama, Kachamota, Lalsidhurkouta, Bara bazal, Koiadigha, Laida, Hashful, Hashumaita, Asmoita, Dilkhama, Lal khama, Kalagura, Chengamura, Chiknal, Kalo saita, Kalosail, Gori bokri, Kahaia sundari, Hargaza, Ghunsi, Maloti, Akhnisail, Kalimekri 77-5, Ratasail Dhona saita, Dholpata, Malbhog, Basmati (D), Sakkorkhora, Tulsimala, Balambiti Jessobalam TAPL-31, Dholasaita, Dular, Hashikalmi, Chandina, Mala, BRI4. Ninety-six genotypes showed highly resistant to bacterial blight (BB) showing the score of 1, 35 genotypes found moderately tolerant under supplemental irrigation condition, 125 genotypes showed highly resistance to bacterial blight in irrigated rice germplasm.

Table 4. Continued.

Parameter	Germplasm
Bacterial leaf streak resistance	Hashikalmi
Rice tungro virus resistance	Latisail, Kataribhog, SadaPankaissoloi, Hbj. Aman VIII, Badshabhog, TAPL-412, Tilockachari, Tulsimanik, Lakshmijota, Badariota, Noroi, Jatramotor, Shirtwsail, Mi-Pajang.
Ufra resistance	Rayada 16-06-1, Sada Pankaich, Rayada 16-011, Rayada 16-013, Rayada 16-05, Rayada 16-06, Rayda 16-07, Rayada 16-08, Bazail, Fukuhunami, Hayakikari, Akiyutaka, Matsuhonami, Dhepi, Gabura, Hatisail, Indrasail, Daudin, Kumari, Dudsar, Badsha bhogh, Lal aman, Jessobalam, Jhingasail, Khirai jail, Nizersail, Patni-23, Rajasail, Sr-26b DA, Tilockachari, Lambosail, Kartiksail, Pankaij, Holidjaran, Modhusail, Bhawalia aman, Lal chamara and Baish binni.
Bakanae resistance	Panati, Nizersail (DA-25)
Green leaf hopper resistance	Jhingasail, Godalaki, Aswina, Dumai, Gadur, Hasmita, DNJ 97, Sailbinni, Ashajus, Golapi, Gabura, Suna Digha(2), Dular, Khorma, Morium
Brown plant hopper resistance	Balam, Gotabazal, Bara bazal, Rajasail-21, Dudsar, Maliabhangor, Tangul, Krishnachura, Digha, Sungwala
White backed plant hopper resistance	Khama 49/8, Laldhan, Begum bitchi, Khawrang, GiringNagpechi, Maitty chang, Boira aman, Kalaraj, Malia bhangor, SR-26-B, Kawya, Bajal, Tara bali
Stemborer Resistance	Bhasamanik, Latisail, Raghusail Badshabhog, Patnai 23, DNJ 97, Joya, Botai, Kali boro, Kerani dhan, Lembur, Tulsimala, Aghnisail, Rajasail, Chanmoni, Boilam, Lohargura, Murari, Jhoria
Gall midge resistance	OB 677, Vellutha cheera, Muktahar (acc 156), Safahar (acc 368) and Koha binni (acc 208) found moderately resistant
Submergence tolerance	Soitedhora, Lohatang, Kumri, Kaliraj, Kaladhan, Hijaldigha, Sada gabura, Khoia motor, Kumragoir and Ashfol. Acc. 4217, 4398, 4399, Kalojoma, DG1-349, Putidepa, Laldepa, Songa Tepi (Acc No. 4217), Atshotti (Acc. No 4398), Muirol, Bhoban and Maityacheng found tolerant at seedling stage under complete submergence. Pathornuti, Sadadangaboro, Jaldairri, Horkoach, Haloi, Bazal, Rajasail found tolerant under medium water stagnation
Anaerobic germination tolerance	Hatisail, Indrasail, Khirari, Joli, Lal aman, Nizersail, Ratasail, Halid jaran, Modhusail, Dharial, Chaita Boro, D. Lia
Tidal submergence Tolerance	Kumragoir, Dudmona
Salinity tolerance	Pokkali, Reyasail, Nonabokra, Uri dhan (*Porteresia coarctata)*, Nonakochi, Sabrimaloti, BR23, Molla digha, Bhawalia, Neppasha, Banoi jhak (3), Bawoi jhak (6), Kumri aman, Kolam, Lal kumari, Pura binni (3), Sungwala, Lambra, Bazal dhan, Kala gura, Chand moni, Goda, Ghori aman, Binni dhan, Guda aman, Boteswar, Begun bichi, Khama rang, Lembur, Lal bini, Halde mldi, Patnai, Latisail and Rajasail were found tolerant against salinity. DWR genotype, Noakhali, Jota bhaulia and Kartiksail 2 were found moderately tolerant at seedling stage. Lambra, Bazail dhan and Kechrail were found tolerant at the reproductive stage.
Drought tolerance	Hashikalmi, Dular, Canthi bakla, N sail, Hashim, Urichedra, Goura kajol, Chini sail, Tall biruin, Sakkar khana, Boaincha biruin
Heat tolerance	Acc. no. 96, 97, 100, 128, 131, 133, 563, 568, 816, 1212, 1532, 1546 and 1688 under net house and acc. no. 104 at field conditions found best tolerant to heat.
Cold Tolerance	Acc. no. 114, acc. no. 177, acc. no. 197 and acc. no. 202 and 472 were found best tolerant to cold. Bhutan (a Bhutanese germplasm) showed better tolerance against cold for both seedling and reproductive stage.
Allelopathy	Kataribhogh, Kartiksail, Jhingasail, Burikatari, Bolorum, Chakulia, Shadadumra, Kola dama, Joli, Rangpuri(sada), Mi-chocho, Biruin (Tola), Balamdhan, Rajasail
High protein	BR5, Baha bhogh, Thakurbhogh, Habiganj Boro II, Hashikalmi, Dular, Ashfol, Birani dhan, Horkoch, Kachra, Jira dhan, IR 1010, Laltupi, Joyosri ghunshi, Banajira, Dhala saita, Hashikalmi, Kartikjhul, Holid jaran, Apchaya, Jamaibhog, Arichadigha, Manik digha 1, Goirol, Bashful, Bawoijhak 4, Bawoijhak 6, MI-Pajang, Chakil, Lema, Niamat, Magoibalam, Matichak, Neda, Molladigha and Boilam.
Popping quality	Highest percentage of popping were found in Kanakchul, Nizersail and Rangabinni
Zn enriched (aromatic)	Sagardhana, Nunia, Binaphul, Begun bitchi, Hatisail, Sakkorkhana, Kalobakri

Important points for efficient utilization of rice germplasm

- The collection of germplasm from home and abroad needs to be continued to enrich the Genebank with more diversity.
- Characterization and evaluation of all of the germplasm should be carried out against the major yield contributing traits and for biotic/abiotic stresses (cold, heat, flood, drought, submergence, water stagnancy, salinity, blast, etc.) and/or grain quality through the morphological and molecular tools. Phenomics should be playing a key role in the characterization of germplasm. All the germplasm accessions should also be fingerprinted with genome-wide high-density markers. These are also needed for duplicate sorting, the establishment of Intellectual property rights and to protect germplasm from biopiracy.
- Developing new varieties from landraces through Pure Line Selection like BR5 and BRRI dhan34.
- The development of pre-breeding materials is a very important task for the Genebank team. "Pre-breeding" is the initial phase of any breeding programme utilizing germplasm.
- QTL identification for different traits and partial/whole-genome sequencing is important for germplasm/Geographical Indication (GI) rice which will be used for the crossing programme. Genome-wide association mapping may be used for the QTL identification from sequencing data which is proven very effective for rice germplasm.
- Development of a biodiversity park where all of the germplasm needs to be grown in respective season over the years and kept open to rice breeders for the necessary selection of pre-breeding materials.
- Documentation of characterized/evaluated germplasm through digital photo and computer database documentation system through appropriate software for different users. From this database, one can retrieve the germplasm with the targeted trait(s) very easily.
- Core collections (a representative sample of the alleles from the entire collection) serve as an entry point to the whole collection and improve the access of the plant breeder, researcher, geneticists, and other users to the germplasm collection.
- Genebank may serve the raw materials for C4 rice development.
- Wild rice may be used for crossing to break the yield ceiling as these are the vast reservoir of beneficial genes and have higher genetic diversity than cultivated rice.
- Development of several Breeding Hub for developing location-specific rice variety by utilizing materials from Genebank.
- Easy supply/exchange of rice germplasm to national/international researchers/ organizations at home and abroad for efficient utilization.

Genebank is reservoir of genes, used in plant breeding. Effective use of genebank in breeding relies on a thorough understanding of the existing genetic diversity and knowledge of the genes present in individual accessions. Knowledge gained through the activities of characterization and evaluation could be used in rice breeding for developing improved rice variety which will ultimately meet the increasing food demand of the country.

Plant breeding interventions

For developing further high yielding varieties by breaking yield ceiling, BRRI breeding programs have undertaken several modernization activities leading to accelerated genetic gain as follows:

Increasing selection efficiency. Selection efficiency of BRRI breeding programmes has been increased through increasing the size of breeding programs with the application of single-seed-descent based rapid generation advancing (RGA) technique and wide-scale application of high throughput molecular markers.

Currently, BRRI breeding programmes are advancing around 1.5 million segregating progenies per year utilizing both greenhouse and field rapid generation advance (RGA) techniques. More or less all breeding programs, including favourable and unfavourable breeding programmes have been transformed from an inefficient and slow pedigree method of breeding towards single seed descent (SSD) based RGA technique enabling two to three generations per year. So far, around 1,26,855 fixed lines have been generated and evaluated in line stage testing (LST) from these segregating progenies. Accelerated breeding cycles will hopefully contribute to achieving desired genetic gain with respect to grain yield, quality, and stress resistance traits in a shorter period of time.

High throughput molecular markers are playing a key role in increasing the selection efficiency of BRRI breeding programs. Low density and high-density molecular markers are routinely being utilized in the breeding programs (Table 5) in a number of interventions like quality checking of parental lines and F_1's using 10-SNP (Single nucleotide polymorphism marker) indica panel, QTL (quantitative trait loci) finger-printing of the parental lines using trait-based SNPs, GBS (genotyping by sequencing) profiling of the parental lines for the determination of sequence-based genetic distance and deploying trait-based SNPs at LST trials (Table 5). So far, QTL fingerprinting has been done for 835 parental genotypes with trait-based SNPs. Confirmation of 8,56,676 F_1's has been done using 10-SNP QC (quality control) panel. GBS profiling has been done for 450 parental genotypes with diversity array technology based sequencing (DArT-Seq) SNPs. QTL fingerprinting data and GBS profiles have been utilized to generate distance matrix in all possible combinations from which high-value elite-by-elite crosses have been accomplished. Around 2,604 genotypes have been assayed with 1k-Rice Custom Amplicon (1k-RiCA) panel and genetic sequence-based breeding values of parental lines have been calculated. Around 29,582 LST lines have been genotyped with key diagnostic SNP markers for tracking useful oligogenic traits conferring different biotic and abiotic stress tolerances and grain quality traits. In the future, BRRI breeding programs will put more focus on the utilization of bioinformatics tools for increasing selection efficiency like genomic selection and selection of potential parents and high-value cross-combinations based on sequence data (Table 5).

Increasing selection intensity. Enlarged breeding programs and wide-scale application of high throughput molecular markers are also contributing to increased selection efficiency in BRRI breeding programs. Selection intensity has also been increased through ensuring a large number of early generation breeding lines entering into multi-environmental yield trials. Around 3500 breeding lines in Observational Yield Trials (OYT) are being evaluated every year in at least three locations.

Increasing selection accuracy. Selection accuracy of BRRI breeding programs has been increased through product profile-based breeding, automation in post-harvest operation, digitalization in data collection, and management, following appropriate experimental design and analysis, ensuring large plot size with replicated trials, increasing number of multi-location trials and appropriate field and post-harvest management (Table 5). BRRI breeding programs are now utilizing Breeding for Results (B4R) software for the integrated data management system. In the case of automation, electronic scale-like Phenoapp, digital weighing-cum-moisture recording device harvest-master, digital seed counting device like Seed Analyzer, non-destructive grain quality data recording device like near infra-red (NIR) analyzer, etc. are being utilized for handling large breeding population. Earlier, breeding lines constituting in regional yield trial (RYT) would have been tested in multi-locations but nowadays multi-environment trial (MET) has been initiated starting from OYT which is efficiently contributing towards increased selection intensity from large breeding trials. Product profiles are a complete set of characters to be present in target varieties for a particular geographical segment. BRRI has developed sixteen product profiles through surveying different value chain actors. Product profiles are contributing to the selection of parents, selection of high-value cross combinations, and the promotional decision of breeding lines from one stage to another. As a whole product profile-based breeding is contributing to increased selection accuracy of breeding programmes.

Cyclic breeding for accumulating yield contributing genes/alleles in the same genetic background. Currently, population improvement is the key concept of BRRI breeding programs. BRRI has started recycling early generation breeding lines with higher breeding values in crossing programs. While crossing between two parents, sequence-based genetic distances are being considered. As per the current concept, around 65% of the rice genes are responsible for grain yield. Like grain yield, plant types are also highly polygenic characters. Hopefully, this recurrent selection through cyclic breeding will contribute to developing high yielding inbred rice varieties to produce enough for the increased population by 2050.

Interventions with biotechnological tools

Utilizing biotechnological tools, BRRI so far has released several rice varieties such as BRRI dhan52, BRRI dhan58, BRRI dhan79, BRRI dhan86, BRRI dhan87, BRRI dhan89, BRRI dhan92, and BRRI dhan96 which are high yielding along with possessing special characteristics. BRRI's capability concerning the application of biotechnological tools in variety development has got momentum with these successes. BRRI has utilized quantitative trait loci (QTL) study, marker-assisted selection (MAS), somaclonal variation, and anther culture techniques to develop the aforementioned varieties (Table 5). Also, BRRI is practicing other biotechnological tools and adopting newer techniques sharply in this domain. However, the Biotechnology division of BRRI already has developed advanced breeding lines containing bacterial blight resistance genes like *Xa4, xa13,* and *Xa21*. This division has cloned the vacuolar ATPase (PVA) gene from *Porteresia coarctata* and developed the construction with *Agrobacterium* LBA4404 which will confer salinity tolerance upon transformation into the rice. Also, this division has developed putative T1 transgenic plants containing salt tolerance *GlyI and GlyII* gene (*Glyoxalase I* and *Glyoxalase II*). Besides, this division is trying to introgress salt tolerance gene *AeMDHAR (Monodehydroas-corbate reductase)* into BRRI rice varieties. Other priority areas of this division are developing high yielding aromatic, low glycemic index, antioxidant-enriched, and C4 rice development. However, it is more likely that timely harnessing the biotechnological tools would support conventional breeding for efficiently improving rice yield and quality along with biotic and abiotic stress tolerance. With this light, this part of the article will discuss briefly how some of the key biotechnological tools can be utilized more efficiently in the future for increasing productivity. However, we will categorize the biotechnological tools in the following three broader areas.

Marker Assisted Selection (MAS). Molecular markers bring crop diversity in breeding programs which largely track desired genes of interest limiting associated linkage drag. A recent study revealed that only half out of sixty well-validated genes and QTLs for disease resistance, grain quality, and abiotic stress were present in 75 elite indica rice varieties paves a huge research opportunity using MAS to explore (Cobb *et al.,* 2019). But this tool is very effective only when there is an oligogenic trait (Amiri Fahliani *et al.,* 2011). A polygenic trait showing continuous variations should not be a choice for MAS. Therefore, to carry out a successful MAS, identification of a major gene or development of robust QTL is very crucial. Transcriptomics technologies could be applied for target gene identification. For identifying QTLs, genome-wide association mapping explores more diversity and has higher cost-effectiveness than bi-parental QTL mapping (Verdeprado *et al.,* 2018). Also, association mapping can track the presence or absence of a gene in a broader genetic context (Cobb *et al.,* 2019). QTL studies often reveal a complex trait without having any major regulating genes could be a choice for genomic selection (GS) where small effect Favourable alleles could be accumulated for desired improvement (Cobb *et al.,* 2019). GS establishes an association between genome-wide markers and phenotypes. It estimates individual loci value and eventually predicts the genetic value of an untested population (Wang *et al.,* 2018).

Tissue culture. Among tissue culture techniques, anther culture poses to be very effective allowing immediate fixation of homozygosity through diploidization often by spontaneous chromosome doubling (Ruwani *et al.,* 2018). Whereas, embryo rescue, another potential tissue culture technique, can successfully grow the plants achieved from intervarietal, interspecific and intergeneric, or more distantly related crosses and bring novel genetic material and traits in breeding programs. These crosses could otherwise generate abortive embryos (Kausch *et al.,* 2016). Traits having limited or no natural variation eg. sheath blight resistance in rice can be created using somaclonal variation (SV) which induces genetic or epigenetic changes in plant cells and tissues during culture. These induced variations can be utilized if found beneficial (Anil *et al.,* 2018).

Genetic transformation. Genetic engineering is one of the key biotechnological tools that allows transferring novel traits to rice from evolutionary distant plants, even from fungi, viruses, bacteria, and animals. It is being used world-wide including in Bangladesh to make rice plant stress-tolerant and nutritionally enriched. Among a number of DNA delivery methods available, *Agrobacterium* and biolistic mediated transformation remain pivotal (Sah*et al.,* 2014). However, genetically transformed rice varieties are more likely to take a longer period of time to get released due to its foreign DNA and subsequent lengthy and stringent biosafety regulations. Genome editing is giving hope to ease up the regulation since foreign DNA will be excluded from the host genome. CRISPR/Cas9, among a variety of genome editing tools, claims maximum acceptance due to its accuracy, simplicity, and robustness (Mishra *et al.,* 2018). We have already started genome editing interventions through CRISPR/Cas9 technique for the development of high-yielding aromatic, blast-resistant, and BPH resistant rice varieties.

Hybrid rice breeding interventions

Hybrid rice technology is among the greatest innovation, which can increase productivity readily upon being adopted. It has at least 15-20% higher yield potential compared to high yielding inbred rice varieties using the same inputs. Hybrid rice varieties have proved the ability to perform better under unFavourable conditions in varying environments like drought, cold and saline conditions (Singh *et al.,* 2009). Furthermore, this technology increases farm incomes and stabilized grain prices for consumers (Spielman *et al.,* 2012). Hybrid rice plays one of the key components of food security, especially in poor countries in the tropics, where the population is increasing rapidly, and eventually, the cultivable land is decreasing (Santiaguel and Quipot, 2012). Hybrid rice greatly contributed to boosting rice production in China (Spielman *et al.,* 2012). This technology has attracted the attention of research leaders and policy-makers in many Asian countries for breaking the yield ceiling in rice production (Hossain *et al.,* 2003). The 'father of hybrid rice', professor Longping Yuan mentioned that Bangladesh could be self-sufficient in food grains through the adoption of hybrid rice technology (Yuan, 2012).

Hybrid rice research and development program has been undertaken since the last couple of decades at BRRI with technical support from the International Rice Research Institute (IRRI) and financial support from Bangladesh Agricultural Research Council (BARC) aimed to meet the extra food for the growing population of the country (Rashid *et al.,* 2011). Meanwhile, BRRI developed seven hybrid rice varieties, of which four varieties for Boro and two varieties for Transplanting Aman (T. Aman), and one variety for Transplanted Aus (T. Aus) season. The average yield potentiality of Boro hybrid rice varieties is more than 9.0 t ha^{-1} whereas T. Aman hybrid rice varieties give more than 6.5 t ha^{-1}. The only released T. Aus hybrid rice variety from BRRI has a yield potential of 6.5 t ha^{-1}.

To date, almost all of the registered hybrid rice including BRRI hybrids are suitable for Favourable rice type ecosystems (SCA, 2020). Therefore, more emphasis is needed to develop climate-smart rice hybrids for meeting the uprising food demand of the nation. If it is not possible to develop rice hybrids tolerant in stress-prone environments /ecosystems within 2030, then we can expand hybrid rice cultivation areas. It is observed that four specific rice types such as Favourable Boro (short duration), Favourable Aman, Upland rice, and T.Aus rice types are suitable for hybrid rice intensification (Table 3). The yield gap for Favourable Boro (short duration), can be minimized by utilizing hybrid rice varieties especially BRRI hybrid dhan3 and BRRI hybrid dhan5. We need to further increase hybrid rice cultivation in Favourable Boro (short duration) rice type by 36.5% to fulfill the yield gap. Likewise, the yield gap during favourable Aman season can be nullified byadditionally increasing the cultivation of BRRI hybrid dhan4 and BRRI hybrid dhan6 by 30%. Cultivation of BRRI hybrid dhan7 can be further increased by 30% in the upland rice and 36.8% in T. Aus area to reach the target yield by 2030 (Table 3).

Hybrid rice technology is the specialized approach compared to inbred rice technology which needs a sufficient number of skilled manpower to conduct research and development, seed production, promotion, and dissemination activities properly. More expert personnel and associates are needed under the Hybrid rice research division of BRRI to conduct hybrid rice research and development activities as per the demand of stakeholders.

The development of new hybrid varieties for changing agro-climatic conditions can accelerate productivity. Developing new hybrid varieties with high yield potential needs to employ several breeding practices for changing ideotypes and exploiting maximum heterosis. Super high yielding hybrid rice varieties could be developed through, 1) increasing plant biomass through increasing plant height from semi to tall and then tall to super tall for the yield increase of 12 to 14, and then further to 18 t ha^{-1}, respectively; 2) Developing highly photosynthetic efficient plant population by morphological improvement; 3) exploring more heterosis from indica/japonica combination and favourable genes/QTLs to enhance lodging tolerance; and, 4) improving harvest index to 0.50-0.55 (Ma and Yuan, 2015). The hybrid rice group of BRRI has set the target to develop hybrid rice varieties having at least 2 t ha^{-1} yield advantage over the existing best varieties along with better grain qualities. Doing so, the existing hybrid rice research facility of BRRI should be strengthened to contribute to the future food security of the country.

It is a tremendous task to fulfill the targeted demand. It needs to develop a well-trained target group for developing and multiplying parental lines, hybrid rice seed production, processing, storing, and marketing. Therefore, to meet the demand, BRRI should take initiative to strengthen hybrid research and collaborate with the public and private entrepreneurs at the national and international levels. BRRI needs to establish a well-equipped Hybrid Rice Research Center like China and the Philippines, which could help to develop a skilled group to take over the future challenges (Table 5).

Table 5. Mapping the action plans for achieving the target GYP for three decades.

Program	2021-2030	2031-2040	2041-2050
Application of population improvement strategy for accelerated genetic gain.			
Application of molecular marker assisted selection			
Application of QTL fingerprinting and GBS profiling			
Development of genomic selection			
Application of genomic selection			
Enhanced automation and digitalization in genotypic and phenotypic data management			
Utilizing phenotypic automation and digitalization in genotypic and phenotypic data management			
Development and utilization of modern seed processing, storage and breeding germplasm management system			
Utilization of anther culture, somaclonal variation and embryo rescue			
Enhancement of genetic engineering and genome editing facility			
Utilization of genome editing and genetic engineering			
Enhancement of OMICS facilities			
Utilization of OMICS			
Increasing hybrid rice seed growers for enhanced adaptation	150	300	500
Establishment of molecular laboratory for hybrid rice development			
Application of molecular techniques in hybrid rice development			
Enhancement of seed processing and storing facilities for hybrid rice development			
Modernization of existing genebank and establishment of an underground genebank			
Development of rice germplasm characterization/ evaluation facilities (Net house/ Phytotron)			
Complete/ partial sequencing of 5300 native germplasm			
Digitalization of genebank management system (software/ website for genebank database development)			
Manpower development			

CONCLUSIONS

We fragmented rice areas of Bangladesh into 17 different rice types based on different rice ecosystems and pressing needs and set different targets for each, so that, combinedly we can reach an average rough rice yield target of 9.11 tha^{-1} by 2050. We compared the yield targets by 2050 and the yield of top-yielding rice varieties in Bangladesh by 2020 across the rice types to understand the current position of our varietal improvement programs. Eventually, we sorted out how much improvement is needed in each rice type which will be implemented in varietal development programs of the country in the coming years. BRRI, the leading institute for rice research in the country which so far has released 106 inbred and hybrid rice varieties will further accelerate its breeding programs through combined genetic interventions like population improvement through cyclic breeding and high throughput molecular markers, bioinformatics, genome editing, genetic transformation, germplasm utilization through genome-wide molecular markers and phenomics and development of super hybrid rice. There are specific scopes of increasing the yield potential of rice varieties for cold-tolerant (Northern and western), Saline Boro, Favourable Boro (long duration), etc. Addressing the challenges with combined genetic interventions, BRRI will achieve yield targets in all respective areas by 2050.

RECOMMENDATION

A combination of available genetic interventions like population improvement through cyclic breeding, genomic selection, marker-assisted selection, genome editing, genetic transformation, germplasm utilization through genome-wide association study and phenomics, and development of super hybrid rice is the only option for achieving target GYP by 2050.

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AUTHORS' CONTRIBUTION

SMHAR generated idea; SMHAR, PLB, ESMHR and KMI coordinated the research; SMHAR, KMI and MUS developed methodology; MSR and MSK provided scientific insights; SMHAR, KMI, NMFR and MARS gathered data; NMFR and MAAM carried out analysis and synthesis; SMHAR, PLB, ESMHR and KMI did the writings for all versions of the manuscript; MSR and MARS performed critical review and editing; All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

A version of the paper was published in a book "Doubling Rice Productivity in Bangladesh" in 2020 by the Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh to commemorate BRRI's 50th anniversary. The Bangladesh Rice Journal has prior knowledge of the book publication and does not see any conflict of interest.

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Enhancing Rice Productivity in the Unfavourable Ecosystems of Bangladesh

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ABSTRACT

Rice is cultivated in the three seasons (Aus, Aman, and Boro) across four ecotypes, including irrigated, rainfed upland, rainfed lowland, and deep water in Bangladesh. Rice farming in unfavourable ecosystems is highly exposed to abiotic stresses and extreme weather events (floods, droughts, storm surges, and cyclones), and its performance is frequently affected by the multiple-stresses and extreme weather events. Besides, the increasing demand for rice for the growing population and decreasing scarce resources, including arable land and fresh-water for irrigation aggravated the concern about sustainable rice production systems under future conditions. Thus, the paper aimed to exploit unfavourable ecosystems to increase total rice production for meeting future demand. Secondary data were analyzed to achieve the objectives of the study. BR23, BRRI dhan40, BRRI dhan41, BRRI dhan47, BRRI dhan53, BRRI dhan54, BRRI dhan61, BRRI dhan67, BRRI dhan73, BRRI dhan97, BRRI dhan99, BINA dhan-8 and BINA dhan-10 are resilient to salinity. Besides, BRRI dhan56, BRRI dhan57, BRRI dhan66, BRRI dhan71, and BRRI dhan83 are resilient to drought, and BRRI dhan51, BRRI dhan52, BRRI dhan79, BINA dhan11, and BINA dhan-12 are tolerant to submergence. The BR18, BRRI dhan36, BRRI dhan67, and BRRI dhan69 are some-extent resilient to cold. The research has been continuing for developing further stress-tolerant higher yield potential rice cultivars for unfavourable ecosystems. The increased adoption of currently available stress-tolerant rice cultivars has the potential to give a substantially higher yield than that of locally popular rice cultivars in the unfavourable ecosystems. Therefore, the dissemination of stress-tolerant cultivars to 75% of total rice cropping areas of saline (0.37 Mha), submergence (1.08 Mha), and drought (2.94 Mha) ecosystem may contribute to increasing rice production in the ecosystems by 1.26 MT, 3.45 MT, and 9.18 MT, respectively. Resulting from that 13.89 MT rice will be added to the national rice basket in 2050. The policy supports are needed to strengthen for developing and rapid dissemination of the stress-tolerant cultivars in the unfavourable ecosystems for meeting the increased demand of rice of the growing population under future conditions.

Key words: Rice, unfavourable ecosystem, salinity, submergence, drought, climate change.

INTRODUCTION

Bangladesh is a low lying agrarian country. The land surface of the country is mostly floodplain (80%), a few areas under terraces (8%), and hills (12%) (FAO, 1988). Besides, the country belongs to a favourable environment for growing rice across the year in the three overlapping seasons (Aus, Aman, and Boro) and four ecotypes included irrigated, rainfed upland, rainfed lowland, and deep water. Boro rice is a photoperiod insensitive irrigated rice grown in the dry season (DS: December-March). Aus rice is also photoperiod insensitive and mostly grown in rainfed conditions in the early wet season. Transplanted Aman is a mostly photoperiod sensitive rice grown in the wet season under rainfed conditions (Uddin, 1993). However, rice farming in the country, in particular in unfavourable ecosystems is frequently affected by abiotic and biotic stresses, including global warming lead extreme weather events (drought, floods, tidal surge, and cyclones). The abiotic stress in particular (i) salinity in the coastal region, (ii) submergence in the low-lying and basin areas, and (iii) tidal submergence in the non-saline coastal region, prevails in the country. Besides, drought in the

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dry season, early wet season (EWS: April-June) and wet seasons (WS: July-September), and cold in the Boro season in the north-west and north-east (Haor) regions also prevails. The arable area under drought-prone ecosystem (4.20 M ha) was higher followed by rainfed low land (3.20 M ha), submergence (2.80 M ha), and salinity (1.2 M ha) (Table 1). Besides, the country was affected by over 200 extreme weather events across the last two decades, consequently per year economic loss of the country was about 1% of total national GDP (Kreft *et al.,* 2016).

Although a bulk of studies were carried out for assessing the impact of climate and environmental change on the performance of rice and non-rice crop farming (Yu *et al.,* 2010; Ruane *et al.,* 2013; Thurlow *et al.,* 2012; Kabir *et al.,* 2018a) and farmers adaptation to climate change (Kabir *et al.,* 2016; Kabir *et al.,* 2017a; Kabir *et al.,* 2017b; Kabir *et al.,* 2017c; Kabir *et al.,* 2018b; Kabir *et al.,* 2019; Kabir *et al.,* 2020) in Bangladesh, in particular in the stress ecosystem. However, none of the studies found to explore the potential of the unfavourable ecosystems to contribute to the national rice basket under future conditions (2030, 2040 and 2050). Thus, the paper explores the prospects and potential for increasing and sustaining rice productivity in unfavourable ecosystems.

METHODOLOGY

The data were collected from different published and unpublished secondary sources, including journal articles, reports, and presentations of BRRI (Bangladesh Rice Research Institute), BARI (Bangladesh Agricultural Research Institute), BINA (Bangladesh Institute of Nuclear Agriculture), IRRI (International Rice Research Institute), SRDI (Soil Resource Development Institute), FAO (Food and Agriculture Organization of the United Nations). The adoption of stress-tolerant rice cultivars and their potential performance in the saline, drought, and submergence ecosystems under future conditions was extrapolated based on(i) current adoption status of stress-tolerant cultivars and (ii) potentiality of currently available stress-tolerant cultivars for those ecosystems. Besides, the potentiality of enhancing rice production in the other ecosystems, including tidal non-saline, haor, rainfed lowland, upland, and Charland.

Table 1. Arable area under unfavourable ecosystems in Bangladesh.

Ecosystem	Existence of other stress	Area (M ha)*
Salinity	Tidal submergence in wet season, Heat and drought stress at reproductive phase of Boro rice	1.20
Flash flood (submergence)	Flash flooding at vegetative phase of T. Aman rice	2.00
Tidal submergence	Heavy siltation and turbulence	0.80
Haor (Deepwater rice)	Drought at vegetative phase	0.80
Drought	Heat at reproductive phase	4.20
Rainfed lowland	Flood and water stagnation at vegetative phase and drought at reproductive phase	3.20
Upland	Drought at vegetative phase and heat stress at reproductive phase	0.20
Charland	Drought and submergence at vegetative phase and heat stress at reproductive phase	0.83
Low temperature#	Cold at seedling stage of Boro rice at North-East and North-West region and reproductive phase of Boro rice at North-East region (Haor)	2.00
High temperature #	Heat at flowering stage of long duration Boro, Upland Aus and short duration T. Aman	--

*M ha= Million hectare; Area adapted from Kabir *et al.,* 2018c; #This is not an ecosystem rather stress condition.

RESULTS AND DISCUSSION

This section presents the status of currently available rice technologies for unfavourable ecosystems. Thereafter, constraints of rice farming and the necessities for improvement of the technologies for those ecosystems were presented. Besides, the extrapolated potential contribution of saline, submergence, and drought ecosystem in 2030, 2040 and 2050 in Bangladesh was also presented in the section.

Status of rice cultivars for unfavourable ecosystem

Table 2 presents the progress in rice breeding in developing cultivars for unfavourable ecosystems in Bangladesh.

Bangladesh Rice Research Institute (BRRI) and Bangladesh Institute of Nuclear Agriculture (BINA) have developed about 33% variety for stress ecosystems (Salam *et al.,* 2019). Most of them are higher yield potential and stress-resilient rice cultivars such as BR23, BRRI dhan40, BRRI dhan41, BRRI dhan47, BRRI dhan53, BRRI dhan54, BRRI dhan61, BRRI dhan67, BRRI dhan73, BRRI dhan97, BRRI dhan99, BINA dhan8 and BINA dhan10 for saline ecosystem. Besides, BRRI has developed BRRI dhan56, BRRI dhan57, BRRI dhan66, BRRI dhan71, and BRRI dhan83 for the draught ecosystem. BRRI dhan51, BRRI dhan52, BRRI dhan79, BINA dhan11, and BINA dhan12 were released for submergence ecosystem. BR18, BRRI dhan36, BRRI dhan67, and BRRI dhan69 are some-extent resilient to cold. Large-scale dissemination of the cultivar potential to enhance rice production for ensuring rice security and increasing farm income is needed in the fragile ecosystems (Table 2).

Saline ecosystem

The region consists of 147 upazilas of 19 districts covering about 32% of total areas of the country (BBS, 2018) of which 48 upazilas of 12 districts are directly exposed to the Bay of Bengal. The exposed coastal districts are highly vulnerable to salinity intrusion and extreme weather events (Bala and Hossain, 2010).

Table 2. Progress in rice breeding in developing cultivars for unfavourable ecosystems in Bangladesh.

Unfavourable ecosystem	Rice cultivars for unfavourable ecosystems*
Salinity	BRRI dhan47, BRRI dhan61, BRRI dhan67, BRRI dhan97, BRRI dhan99, BINA dhan8, BINA dhan10 for Boro season. BR23, BRRI dhan40, BRRI dhan41, BRRI dhan53, BRRI dhan54, BRRI dhan73, BRRI dhan78 for T. Aman season
Flash flood submergence	BRRI dhan51, BRRI dhan52, BRRI dhan79, BINA dhan11, BINA dhan12
Tidal submergence	BRRI dhan44, BRRI dhan76 and BRRI dhan77 for non-saline condition
Haor (Medium deep area)	BRRI dhan91
Drought	BRRI dhan56, BRRI dhan57, BRRI dhan66 and BRRI dhan71
Rainfed lowland	BR10, BR11, BR22, BR23, BR25, BRRI dhan30, BRRI dhan31, BRRI dhan32, BRRI dhan46, BRRI dhan49, BRRI dhan72, BRRI dhan75, BRRI dhan87
Upland	BR21, BR24, BRRI dhan27, BRRI dhan42, BRRI dhan43, BRRI dhan65, BRRI dhan83 (for B. Aus) and BRRI dhan26, BRRI dhan48, BRRI dhan55, BRRI dhan82, BRRI dhan85 and BRRI dhan98 (for T. Aus)
Charland	All drought tolerant, short duration and submergence tolerant varieties
Low temperature (Cold stress)#	BR18 and BRRI dhan36 (tolerant at seedling stage); BRRI dhan67 and BRRI dhan69 is tolerant at reproductive phase
High temperature (Heat stress)#	BRRI dhan62 is moderate tolerant at flowering stage

*Source: http://knowledgebank-brri.org/; http://www.bina.gov.bd/; #This is not an ecosystem rather stress condition.

The Soil Resource Development Institute (SRDI) reported about 1.056 million ha arable areas affected by different degrees of salinity in 2009 from only about 0.833 in 1973. The salinity affected area increased by 26% over the last four decades (1973-2009) (SRDI, 2010).

The slightly (4.1-8.0 dS m^{-1}) saline affected area decreased by 153,000 ha during 1973-2009. However, moderate strong (8.1-12.0 dS m^{-1}) to strong (12.1-16.0 dS m^{-1}) and very strong (>16.0 dS m^{-1}) salinity affected area increased by 272,000 ha and 62,000 ha, respectively during 1973-2009. Besides, low to very slight (2.0 – 4.0 dS m^{-1}) salinity affected area increased by 41,000 ha during 1973-2000. The salinity intrusion dynamics in the arable area indicate that soil salinity in the arable area in Bangladesh has been increasing both vertically and horizontally over time (1973-2009) (Table 3). Despite the environmental limitation, the coastal region contributes about 25% of total rice production to the national rice basket from about 28% of the total cultivable land of the country (BBS, 2019).

Constraints of cropping for saline ecosystem

The soil salinity and lack of fresh-water for irrigation are the first and foremost constraints for increasing crop production in coastal areas through introducing rice and non-rice crops in the dry and early wet season (Kabir *et al.,* 2016; Kabir *et al.,* 2019). Besides, extreme weather events, in particular, drought and heat drove moisture stress, and torrential rain-driven water stagnation from dry to early wet season substantially affected the performance of rice crops in the region (Kabir *et al.,* 2016; Kabir *et al.,* 2019). However, Aus and Boro rice are more resilient to those extreme weather events than non-rice crops (Moniruzzaman *et al.,* 2020). Moreover, tidal surge, storms, and depression driven torrential rain frequently affected crops farming and livelihoods across the years. Furthermore, excess moisture in the soil is also a constraint for timely sowing non-rice dry season crops in coastal regions (Kabir *et al.,* 2016; Kabir *et al.,* 2019). Finally, blockage drainage canals and tidal flooding in the low-lying areas limit the potential for non-rice cropping in the areas of the coastal region.

The rice is saline sensitive crop and the yield of sensitive cultivars decreased by 12% in the soil having salinity over 3 dS m^{-1} (Mass and Hoffman, 1977). The yield of sensitive cultivars decreased by 50% in the soil with salinity 6 dS m^{-1}. Besides, even the yield of saline tolerant cultivars reduced by 35-40% in the soil with 12.5 dS m^{-1} salinity compared to non-saline soil (Rana, 1985). However, the development of saline tolerant crop cultivars is difficult due to the dynamic nature of salt stress and a broader range of plant responses to salinity at different growth stages (Munns and Tester, 2008).

Due to the above-mentioned constraints, fallow in the dry season followed by fallow in the early wet season and rice in the wet season is the most dominant cropping pattern in the coastal region. This followed by rice in the dry season followed by fallow in the early wet season and rice in the wet season is the second most dominant cropping pattern in the coastal

Table 3. Status of salinity affected areas in the coastal Bangladesh.

Year	Salinity class and level (dS m^{-1}) and area (000′ ha)				
	S1: 2-4	S2: 4.1-8	S3*: 8.1-16	S4: >16	All
1973	287.37	426.43	79.75	39.90	833.45
2000	289.76	307.20	336.58	87.14	1020.80
2009	328.43	274.22	351.69	101.92	1056.30

Source: Adapted from SRDI, 2010, *S3 = S3 + S4 (8.1-12 to 12.1-16.0 dSm^{-1}), S1 (2-4 dS m^{-1}) = Non saline to very slightly saline, S2 (4.1-8 dS m^{-1}) = Very slightly to slightly saline, S3 (8.1-12 dS m^{-1}) = Slightly to moderately saline, S4 (12.1-16 dS m^{-1}) = Moderately to strong saline and S5 (>16 dS m^{-1}) = Strongly to very strong saline region (Rashid *et al.*, 2017 and Ibrahim *et al.*, 2017). The cropping intensity (159%) is largely lower than the national average cropping intensity (197%) in the country. Besides, per hectare yield of rice in the Aus (2.19 t ha^{-1}) and Aman (2.28 t ha^{-1}) season in the coastal district was notably lower than the yield of the rice crops (Aus 2.56 t ha^{-1} and Aman 2.53t ha^{-1}) in the favorable ecosystem. However, despite the adverse consequence of salinity, the yield of HYV Boro (3.74 t ha^{-1}) in the coastal district was slightly lower than the national average yield of HYV cultivars in Boro season (3.91 t ha^{-1}) (BBS, 2018). It may be because of the adverse consequences of salinity is offset by the Na^+ existed that in the coastal saline soil as the lower concentration (<3 dS m^{-1}) of Na^+ is beneficial for the growth and development of plants (Idowu and Aduayi, 2007). The result indicates that there is potential for increasing crop production in particular rice production through both the horizontal (area expansion) and vertical (adoption of stress-tolerant cultivars and recommended management) approaches.

Prospect and potential of rice production in saline ecosystem

The adoption of salt tolerant T. Aman cultivars such as BR23, BRRI dhan40, BRRI dhan41, BRRI dhan53, BRRI dhan54, BRRI dhan73, and BRRI dhan78 with recommended management has the potential to give a better harvest of rainfed wet-season rice in the coastal ecosystem. Similarly, adoption of salt-tolerant Boro cultivars such as BRRI dhan47, BRRI dhan61, BRRI dhan67, BRRI dhan97, BRRI dhan99, BINA dhan8, and BINA dhan10 with recommended management practice has substantial potential to give notable yield advantage over currently popular Boro cultivars in the coastal region. It was reported that the salinity tolerant cultivars (e.g., BRRI dhan54, BRRI dhan73, BRRI dhan67, and BINA dhan10) gave a 2-14% yield advantage over locally adopted popular sensitive varieties (BR11, BRRI dhan28) at saline hotspots (4.0-10.1 dS m^{-1}) in the Satkhira and Khulna region (BBRI 2017, BRRI 2018). The overall adoption of saline tolerant varieties in the coastal region was 28% and the variety gave about a 7% yield advantage over non-saline modern cultivars (Sarkar and Bhandari, 2018).

The chemical, biological, and agronomic or combining both might reduce the reclamation time of commencing cropping in the salinity-affected arable areas (Rehman *et al.*, 2016). Besides, the potential soil toxicity may be reduced for improving the performance of the crop in the saline ecosystem through amending gypsum and other organic and inorganic fertilizers (Rehman *et al.,* 2016). However, the reclamation approaches are costly and time-consuming as well as mostly beyond the farmers' knowledge. Therefore, the development of saline tolerant cultivars is considered as feasible and more productive than the reclamation approaches. The currently available saline tolerant rice cultivars (Table 2.) are the potential to give expected yield in the slightly saline soil (4 dS m^{-1}) to moderate saline soil (12.0dS m^{-1}) that is about 75% of the total salt-affected areas in the country (SRDI, 2010) (Table 3). Besides, despite salt sensitivity, it is feasible to grow rice instead of non-rice crops in the first reclamation soil due to its inherent potential to grow under flooded conditions, because the standing water subsides the capillary rise of salinity to affect crops (Bhumbla and Abrol, 1978).

The rice production potential of the saline ecosystem was extrapolated based on the above-discussed potential of the ecosystem for ten years' interval up to 2050 considering the baseline production in 2015. The rice production in the saline ecosystem might increase by 11.75% by 2050, respectively subject to the dissemination of the saline tolerant rice cultivars in 75% of total salinity affected areas up to 12dS m^{-1} (Table 4). The contribution of the ecosystem in the national rice basket might further increase by adopting recently released salinity tolerant rice cultivars such as BRRI dhan97 and BRRI dhan99. It was due to the cultivars are potential to give 3.93-6.56 t ha^{-1} even under saline condition, increased the yield to 7.10 t ha^{-1} under non-saline condition. It is also the case that the salinity resilience of both the varieties (14-15 dS m^{-1} for seedling stage up to three weeks and 8-10 dS m^{-1} from vegetative to reproductive phase) are largely higher compared to currently popular saline tolerant BRRI dhan67 (12 dS m^{-1} for seedling stage up to three weeks and 8 dS m^{-1} for whole growth).

Steps need to be implemented for achieving the extrapolated target of increasing rice production

Firstly, the higher yield potential and salinity tolerance (up to 12 dS m^{-1} for whole growth period) rice cultivars need to be developed through implementing classical and biotechnological techniques and disseminated up to 75% of total salinity affected areas in Boro season in the coastal ecosystem. It can be noted that the currently available rice cultivars are tolerant of 8.0-10.0 dS m^{-1} salinity stress.

Secondly, access to fresh-water for irrigation needs to ensure achieving the dissemination goal of Boro rice for enhancing the rice production contribution of the ecosystem. The river water directly can be applied to Boro rice through shifted transplanting time of the rice crop early since the water salinity of some coastal rivers remains below the threshold tolerance of rice (<4.0 dS m^{-1}) from mid-June to mid-February. Besides, trapping river water in the drainage canals by December can be used for irrigation in the Boro rice. Moreover, improved irrigation water management techniques may help to optimize the use of scarce freshwater resources to achieve the production target.

Finally, the sensitive modern and local rice cultivars should be replaced by higher yield potential saline tolerant cultivars through strengthening extension supports in ecologically unfavourable regions.

Flash flood submergence ecosystem

Heavy rain and tidal surge caused by submergence in the low-lying areas in the wet season is a common phenomenon in Bangladesh (Dewan, 2015; Rahman and Zhang, 2016). Hydrological features including low elevation of lands, criss-cross river networks, high monsoon rainfall, and location in low-extreme of some mighty rivers of India and Himalayas make the country highly vulnerable to flooding. More than 2.5 M ha of rice lands are exposed to floods, of which 1.0 M ha are highly vulnerable to flooding (FAO, 2001; Gumma *et al.,* 2012). Every year one-fifth of the total arable lands of the country are affected by different degrees of floods. As a result, the country incurs a loss per year of about BDT 4.0 billion and 4% of total rice production (Bairagi and Bari, 2015).

Table 4. Extrapolated rice production through adoption of resilient cultivars in the coastal saline ecosystem of Bangladesh.

Item	Base year (2015)	2020	2030	2040	2050
Rice area increase (M ha) compared to base year	0.222 (28)	0.055 (7)	0.119 (15)	0.119 (15)	0.079 (10)
Rice production increase (MT) compared to base year	0.601 (7.00)	0.161 (1.75)	0.380 (3.75)	0.416 (3.75)	0.301 (2.50)
Projected yield increase over base year (t ha^{-1})	2.71	2.90	3.20	3.50	3.80

Note: 50% of potential yield at non-saline condition was considered for estimating the yield of rice cultivars under moderate saline (8.1 to 12.0 dS m^{-1}) environment. Values in the parentheses are the percentage computed based on the year 2015.

Flash floods frequently affect rainfed lowland rice (RLR) habitats even in the early monsoon to post-monsoon, and the flood prolongs from 2-4 weeks in many areas of the country. Besides, moisture stress (drought) frequently affected the performance of T. Aman rice, in particular in the region of the north-west floods due to decrease rainfall in the post-monsoon months. Currently available submergence tolerant rice cultivars including-BRRI dhan51, BRRI dhan52, BRRI dhan79, BINA dhan11, and BINA dhan12 are tolerant to 2-3 weeks of flash flood submergence at the vegetative phase. Bairagi *et al.* (2018) reported that about 40% of total farm households in the flood-prone areas of north-west Bangladesh adopted the submergence tolerant rice varieties. It was reported that the submergence tolerant cultivars (e.g., BRRI dhan51, BRRI dhan52) produced a 2-14%yield advantage over locally adopted popular submergence sensitive varieties (BRRI dhan44) in Rangpur and Lalmonirhat (BBRI 2017, BRRI 2018). Similarly reported that the submergence tolerant cultivars in the region produced a 1-4 t ha^{-1} yield advantage over other modern cultivars (Bairagi *et al.*, 2018). Besides, BRRI dhan51, BRRI dhan52, BINA dhan11, and BINA dhan12 produced 2-3 t ha^{-1} yield advantage over popular sensitive modern varieties under severe flooding conditions in Rangpur and Lalmonirhat (BRRI, 2017; BRRI, 2018). The adoption of the submergence tolerant varieties, including BRRI dhan51, BRRI dhan52, BINA dhan11, and BINA dhan12 was 21% of the total rice area of the ecosystem and the varieties gave a 6% yield advantage over sensitive modern cultivars (Sarkar and Bhandari, 2018). Therefore, multi-stress tolerance, including submergence and drought is required to combat the increased extreme weather events in future climates. Therefore, the tolerance of the rice cultivars should be increased up to four weeks and recurrent submergence at the vegetative phase, and drought at the reproductive phase. Besides, agronomic management needs to be improved to achieve the yield benefit. Total rice production of the submergence ecosystem was extrapolated based on the above discussed current performance of the rice varieties in the ecosystem. Total rice production in the ecosystem might increase by 15.43% subject to discrimination the submergence tolerant rice cultivars up to 75% of total rice cropping area in the ecosystem (Table 5).

Drought ecosystem

Drought is an environment caused by a lack of precipitation and high temperature for a period. The drought-driven moisture stress adversely impacts on plants, animals, and humans (Warwick, 1975). Although drought is classified as (i) meteorological, (ii) hydrological, (iii) agricultural, and (iv) socioeconomic, they are highly interlinked with each other. The number of days with less

Table 5. Extrapolated rice production through adoption of resilient cultivars in the submergence ecosystem of Bangladesh

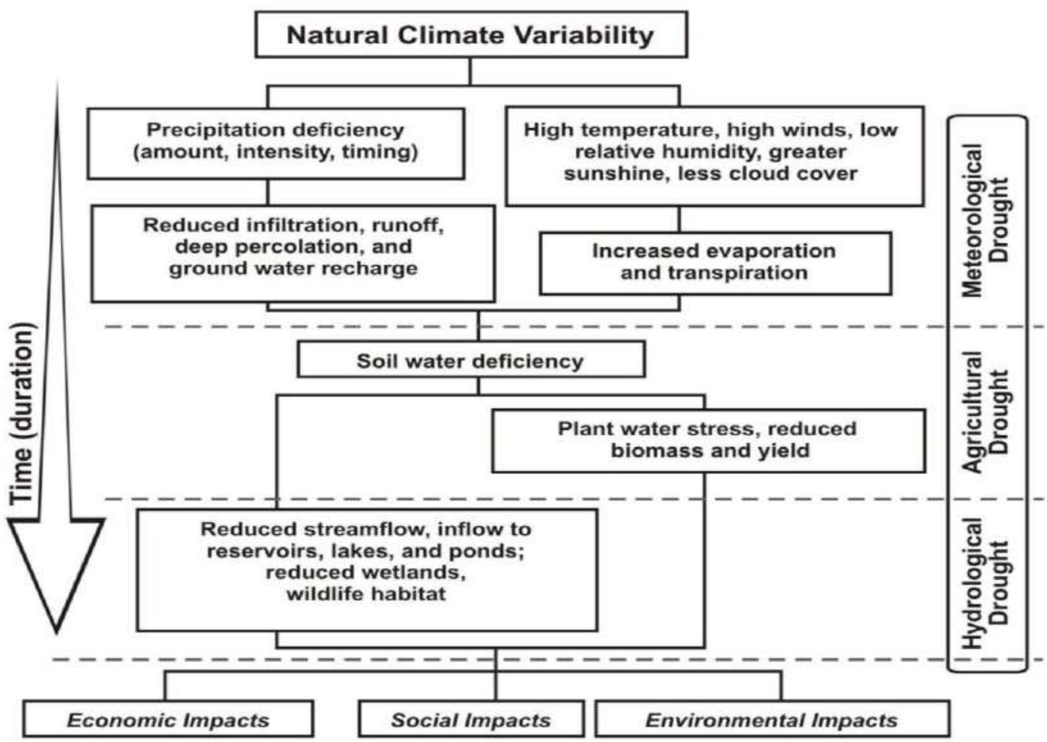
Item	Base year (2015)	2020	2030	2040	2050
Rice area increase (Mha) compared to base year	0.42 (21)	0.28 (14)	0.30 (15)	0.30 (15)	0.20 (10)
Rice production increase (MT) compared to base year	0.974 (6.00)	0.700 (4.00)	0.900 (4.29)	1.050 (4.29)	0.800 (2.86)
Projected yield increases over base year (t ha^{-1})	2.32	2.50	3.00	3.50	4.00

Note: Value in the parentheses is the percentage computed based on the year 2015.

precipitation than some specified threshold is called the meteorological drought. The effect of precipitation for a period on surface or subsurface water supply in the reservoir, lake levels, and groundwater is called hydrological. The moisture deficiency at topsoil and sub-soil caused by meteorological or hydrological drought is called agriculture drought. Therefore, the crop is susceptible to agricultural drought from emergence to maturity. The supply and demand of some economic good with elements of meteorological, hydrological, and agricultural drought are called socioeconomic drought (Wilhite and Glantz,1985). Flow diagram 1 shows the drought series and impacts for generally recognized forms of drought.

The water demand of plants depends on the prevailing weather conditions, the specific plant's biological characteristics, its growth stage, and the physical as well as biological properties of the soil. Water, more than any other factor, is controlling rice growth and development at crucial stages of growth. The crop's ability to withstand drought is necessary for most areas of tropical and subtropical rice cultivation. Therefore, farmers need drought-tolerant varieties for the dryland.

Over 4.2 M ha of rainfed early wet season (Aus) and wet season (Aman) rice area is frequently affected by drought in Bangladesh. The rainfed wet-season rice in the country, particularly in the north-west drought ecosystem is frequently affected by moisture at the reproductive phase due to decrease rainfall in the post-monsoon months (Kabir *et al.,* 2017c).



Flow diagram 1. Sequence of drought occurrence and impacts for commonly accepted drought types (adapted from National Drought Mitigation Center (NDMC):https://drought.unl.Edu/Education/Droughtlndepth/TypesofDrought.aspx/).

Besides, the delay sowing broadcast Aman rice in the deepwater ecosystem is also affected by drought due to early withdrawal of rainfall. Therefore, the development of drought-tolerant rice cultivars is a demand for changing climate conditions.

BRRI has developed some drought tolerant and drought escaping rice cultivars, such as BRRI dhan56, BRRI dan57, BRRI dhan66, BRRI dhan71, and BRRI dhan83 for Aus and Aman season to reduce unexpected yield loss due to moisture stress driven by lack of rainfall or drought. It was reported that the drought-tolerant cultivars (e.g., BRRI dhan56, BRRI dhan57) produced a 6-12% yield advantage over locally adopted popular sensitive varieties (BRRI dhan49 and BINA dhan7) in Rangpur, Nilphamari, Lalmonirhat and Kurigram (BBRI, 2013). Similarly, reported that the current adoption of drought-tolerant cultivars was 5% of the total rice area in the ecosystem, and the variety produced a 1.5% yield advantage over sensitive varieties (Sarkar and Bhandari, 2018). Total rice production of the drought ecosystem was extrapolated based on the above discussed current performance of the rice varieties in the ecosystem. Total rice production in the ecosystem might increase by 21% subject to the dissemination of the drought-tolerant and escaping rice cultivars up to 75% of the total rice cropping area in the ecosystem (Table 6). It can be noted that further moisture stress-tolerant cultivars need to be developed to combat the stress under future conditions.

Tidal non-saline ecosystem

Wet season rice in about 0.8 million ha in the Barishal agriculture region is frequently affected by freshwater tidal submergence. Therefore, farmers of the region cultivate lower yield potential local Aman rice cultivars, as the cultivars are tidal submergence tolerant due to taller plant height and lodging resistance due to strong stem. Besides, the photoperiod-sensitive local cultivars have the potential to produce good yield even in late planting conditions. Moreover, the photoperiod period sensitive and late planting suitable cultivar such as BR23 is also popular Aman variety in the region. However, recently released BRRI cultivars such as BRRI dhan76 and BRRI dhan77 have the potential to produce 1-2 t ha^{-1} yield advantage compared to locally popular local and modern cultivars, including BR23 in the tidal submergence region. Besides, the cultivars are suitable for transplanting in the fields with stagnant water due to taller seedling and plant height and lodging resistant stem. Therefore, large-scale adoption of the cultivars in the tidal submergence region is the potential option to contribute to meeting SDGs.

Haor ecosystem

The haor ecosystem covers an area of around 8600 sq. km in the upper Meghna river basin in northeast Bangladesh. About 0.80 million ha of land are suitable for rice cultivation in the haor ecosystem. The area mostly remains fallow in the wet season due to 0.5 -4.0 meters depth of

Table 6. Extrapolated rice production through adoption of resilient cultivars in the drought ecosystem of Bangladesh.

Item	Base year (2015)	2020	2030	2040	2050
Rice area increase (M ha) compared to base year	0.21 (5)	0.63 (15)	0.84 (20)	0.84 (20)	0.63 (15)
Rice production increase (MT) compared to base year	0.525 (1.50)	1.764 (4.50)	2.520 (6.00)	2.688 (6.00)	2.205 (4.50)
Projected yield increases over base year (t ha^{-1})	2.50	2.80	3.00	3.20	3.50

Note: The advantage of better irrigation management practice was considered in extrapolating Aus and T. Aman yield. Value in the parenthesis is the percentage computed based on the year 2015.

water for 3-5 months. Therefore, Boro rice is mainly cultivated in the haor region in the dry season. The contribution of the rice is 5.3 MT yr^{-1}, which is about 16% of total Boro rice production in the country (BBS, 2019). However, the performance of the Boro rice in the region is affected by floods because of heavy rainfall in the early wet season (April to mid-May) and flows of upstream rivers and mountainous in every 3-4 years interval and damaged the crops substantially. The flash flood is a threat to the food security and livelihood of people in the region. The likelihood of affected by early flash floods is very high for the delay transplanting rice. However, the early transplanting rice suffers from spikelet sterility due to low temperature at the reproductive phase. Therefore, the development of higher yield potential short duration and cold-tolerant (at reproductive phase) rice cultivars are required to overcome both the constraints.

Besides, the area is mostly remained fallow in the wet season due to the unavailability of rice cultivars suitable for growing in the deepwater ecosystem, some of the areas are used for cropping local cultivars of Deepwater Rice (DWR) in the wet season. The taller plant height (> 140 cm) local cultivars survive in the deepwater due to higher elongation capacity. Some of the local cultivars have the potential to elongate up to 5-8 cm d^{-1} for 7-10 days at the vegetative stage. The local cultivars are established about a month earlier in the deep-water ecosystem to improve their survivability. It can be noted that BRRI dhan91 has the potential to give over 3 t ha^{-1} yield in the Deep-Water Rice Ecosystem (DWRE). Therefore, the development of high yielding varieties for medium-deep water condition, pureline selection of existing elongating DWR for deep water environment and large-scale dissemination of the cultivars in the ecosystem may contribute to achieving SDGs.

Rainfed lowland ecosystem

Rainfed lowland ecosystem is the major rice-growing area of Bangladesh. The performance of rice in the ecosystem depends on various conditions including amount, time, and length of rainfall, depth and duration of stagnant water, frequency and time of floods, soil type, and topography. This environment is sub-classified as (i) favourable rainfed, (ii) slightly drought-prone, (iii) slightly submergence prone, and (iv) medium-deep submergence prone.

The favourable rainfed ecosystem is sometimes affected by drought at the reproductive phase due to the early withdrawal of post-monsoon rain. However, BRRI dhan66 and BRRI dhan71 have the potential to give per hectare 4.5-5.5 t ha^{-1} yield in the areas subject to supplementary irrigation application.

The duration of the rainy season is short in the slightly drought-prone ecosystem (whole Barind areas and Rangpur, Lalmonirhat, Nilphamari, and Kurigram district). As result, wet season rice in the sub-ecosystem is sometimes affected by moderate to extreme drought stress. Therefore, photoperiod insensitive drought escaping and drought tolerant cultivars such as BRRI dhan56 and BRRI dhan57 are the potential cultivars to give 4.0-4.5 t ha^{-1} yield in the region.

The duration of submergence persists from 2 to 3 weeks in the slightly submergence-prone sub-ecosystem. The wet season in the sub-ecosystem is prolonged and occurred heavy rain until the reproductive phase of T. Aman rice. The moderate to strong photoperiod sensitive varieties such as BRRI dhan51, BRRI dhan52, and BRRI dhan79 are the potential varieties to give a good harvest in the area.

The duration of submergence persists from 3 to 4 months in the deep submergence prone sub-ecosystem. The photoperiod sensitive and submergence tolerant cultivars such as BRRI dhan91 have the potential to give a good harvest in the ecosystem.

BR10, BR11, BR25, BRRI dhan30, BRRI dhan32, BRRI dhan46, BRRI dhan49, BRRI dhan54, BRRI dhan72, BRRI dhan87, BRRI dhan93, BRRI dhan94, and BRRI dhan95 are suitable for cropping in the favorable rainfed condition. Besides, BRRI dhan56, BRRI dhan57, BRRI dhan66, and BRRI dhan71 are suitable for growing in the slightly drought-prone ecosystem. Moreover, BRRI dhan51, BRRI dhan52, and BRRI dhan79 are the potential varieties to give good harvest at a slightly submergence-prone ecosystem. Finally, BR22, BR23, BRRI dhan34, and BRRI dhan54 are the potential to give good harvest at late planting conditions after drainage out the flood water and BRRI dhan91 is suitable for cropping in the medium-deep condition.

The performance of rainfed rice in the area is frequently affected by submergence and drought and other abiotic stresses. As a result, the livelihoods of millions of farmers have been affected adversely. However, adoption of the above-mentioned cultivars and improving management may contribute to increasing rice production for achieving SDGs.

Upland ecosystem

Upland or dryland rice is grown in rainfed conditions. The rainwater was drained out easily and quickly from the surface of the upland ecosystem. The broadcast rice is cultivated under *Jhum* culture on the slope of the mountain in the upland ecosystem. The photoperiod insensitive, deep-rooted, and to some extent drought tolerantlocal cultivars are mainly cultivated in the ecosystem. The performance of low yield potential local cultivars in the nutrient-deficient soil and stress ecosystem (moisture stress, heat) is quite low. The severe pest infestation, including weeds and application of imbalance fertilizer dose, and poor agronomic practice, also affected the performance of rice in the ecosystem. The extension supports for dissemination of higher yield potential drought-tolerant rice cultivars (such as BRRIdhan42, BRRI dhan43, BRRI dhan65, and BRRI dhan83) and improving current agronomic practice may contribute to increasing rice production for food security in the upland ecosystem. Besides, research should strengthen for developing (i) higher yield potential rice cultivars introducing preferred traits and (ii) further improved crop management practices for the severe stress-prone and nutrient deficient ecosystem.

Charland ecosystem

Chars are the lands that appear as islands on the bank of rivers and the Bay of Bengal due to the dynamics of erosion and accretion in Bangladesh. The active floodplain and non-saline charland soils occur mainly in Kurigram, Lalmonirhat, Sirajganj, Pabna, Rajshahi, Jamalpur, Manikganj, Faridpur, Kushtia, Shariatpur, Madaripur, and Chandpur. Bangladesh has approximately 0.83 million hectares of charland, of which approximately 0.52-0.79 million are cultivable (BARI, 2016). Based on location, charland are of two types-island Chars and attached chars. Island chars are distributed sporadically in the main channel of the rivers and attached chars, which eventually become an integral part of the mainland. Chars' cultivated soils are mainly sandy loam to silty loam, reacting slightly acidic to slightly alkaline, and deficient in nutrients and organic matter. The charland farmers typically cultivated local crop varieties adopting indigenous crop production practices. As a result, crop yield is extremely poor in charland areas. Some problems are associated with lower crop yields at char areas of Bangladesh but drought and scarcity of irrigation facility could hinder profitable cultivation. Introduction of short duration and drought-tolerant modern rice varieties along with improved management practices and different intercropping systems should be the potential for an increase in production and thereby improving the livelihood of the marginal farmers in the charland of Bangladesh.

Low temperature stress (Cold stress)

The daily mean temperature drops below 20 °C is the potential to make different levels of cold injury in rice crops, depending on growth stages. Common cold injuries include failure to germinate, delayed seedling emergence, stunting, and vegetative leaf discoloration; panicle tip degeneration, incomplete panicle exertion, delayed flowering, high spikelet sterility, and irregular reproductive-phase maturity (Yoshida, 1981). The growth and development of Boro rice in Bangladesh are affected by cold injury despite the short winter season in Bangladesh. The mild to severe cold waves (<10-12 °C) during mid-December to late-January frequently affected seedling growth in nursery, vegetative growth after transplanting, and sometimes delayed the transplanting, consequently affected on the performance of the rice crop in the north-western region of the country. Besides, the early transplanting medium growth-duration Boro cultivars (e.g., BRRI dhan28) in the Haor ecosystem are sometimes affected by cold injury (<18 °C) at the reproductive phase during mid to late February, consequently increased rice grain sterility. However, the rice crop could be escaped from unexpected yield loss subject to shifted delay transplanting of the medium-growth-duration rice cultivars after mid-November. Besides, BRRI dhan67 and BRRI dhan69 were identified as moderately cold tolerant at the reproductive phase so that adoption of the varieties in the Haor ecosystem might be reduced unexpected yield loss. Moreover, BRRI has been working on two advanced lines (such as TP16199 and TP7594) for releasing as the variety for the Haor region.

High temperature stress (Heat stress)

The heat stress affects the performance of rice in the tropical and subtropical regions. Although, the typical heat episodes persist for a short period. However, an overlap of heat episodes and critical flowering stage pose a serious threat to spikelet fertility, consequently occur a yield penalty (Jagadish *et al.*, 2007). The persistence of the temperature over 35 °C for two hours at the flowering stage affects anther dehiscence, pollination, and pollen germination, caused rice grain sterility, consequently reduced yield. It can be noted that some exotic Aus rice cultivars such as N22, Kachalath, and Dularis the potential to maintain high spikelet fertility under up to 35-38 °C at the flowering stage.

The heat stress at the susceptible reproductive phase of the rice crop is correlated with water deficit periods in some areas of Bangladesh. The drought and heat combinedly aggravated the moisture stress at the reproductive phase of the rice crop (Wassmann *et al.*, 2009). It was projected that water-deficit stress at rice cropping season might be doubled under future conditions due to decreased precipitation and rise in the temperature in the subtropical climatic region(IPCC, 2007; Wassmann *et al.*, 2009). Besides, global mean warming and heat stress is likely to rise steadily across the 21st century (IPCC, 2013). As a result, the likelihood of affected by spikelet sterility due to moisture stress is a potential threat for rice cropping in the tropical and subtropical regions under future conditions.

Currently, the long duration Boro cultivar namely BRRI dhan29 has been encountering sterility problems due to rise temperature over threshold level both for day (>35 °C) and night 28-30 °C at the flowering stage in late March to April (Shelley *et al.*, 2016). Similarly, the medium duration (~140 days) variety like BRRI dhan28 has also been experiencing heat-induced spikelet sterility when delayed transplanting after potato harvest or grown in the Aus season. The short duration T. Aman varieties (BRRI dhan33, BRRI dhan39, BRRI dhan75) are vulnerable to heat stress poses driven spikelet sterility due to rising temperature at the flowering stage of the cultivars (September to October).

The shifting of transplanting time of Boro rice early and delaying the short duration T. Aman rice varieties might help to escape encountering over threshold temperature at the flowering stage. Besides, the development and dissemination of heat-tolerant rice varieties is a viable strategy to overcome the rising temperature and heat stress-driven challenges (Challinor*et al.*, 2014). Moreover, the adverse impact of heat stress might be escaped through developing early morning flowering potential rice varieties. BRRI research on the development of heat-tolerant rice varieties through introgression heat-tolerant trait on BRRI dhan28 and BRRI dhan29 at yield is at evaluation stage. Besides, BRRI is expected to develop heat tolerance and early morning flowering (EMF) potential cultivars by the next 2-3 years.

Extrapolated rice area and production in Bangladesh

Table 7 presents extrapolated rice production increase through the adoption of stress-tolerant rice cultivars in the salinity, submergence, and drought ecosystems in Bangladesh. There is potential to add about 13.89 MT of rice to the national rice basket in 2050 subject to introduce stress-tolerant rice cultivars in 75% of total area of salinity, submergence, and drought ecosystems in the country.

Actions for achieving rice production increasing goal in the unfavourable ecosystems of Bangladesh

Table 8 lists required research and upscaling activities for increasing rice area and production in unfavourable and stress environments. Firstly, the gravity of stress of each ecosystem should be characterized for developing stress-resilient cultivars and component technologies for the unfavourable ecosystems. The ecosystem characterization activity will have been continued across future conditions. It is due to the frequency and intensity of the stresses have been increasing over time. The research for developing stress-tolerant rice cultivars and management practices have to be continued for combating the adverse consequences of biotic and abiotic stresses on the performance of rice crops. Besides, policy supports are required for developing infrastructure, in particular fresh-water reservoirs and drainage canals for reducing water stagnation. The policy supports are also needed for strengthening research and extension activities for developing and disseminating the technologies to the respective unfavourable ecosystem.

Finally, varietal demonstration will have to be set up at farmers' fields in collaborations with the Department of Agricultural Extension (DAE) during the first half of each decade. The extension linkage will be needed to develop for setting large-scale and mass demonstrations on the most stress-resilient rice cultivars and stress management technologies at farmers' fields in the stress ecosystems across the country during the second half of each future decade.

Table 7. Extrapolated rice production through the adoption of stress-tolerant cultivars in the salinity, submergence, and drought ecosystems in Bangladesh.

Item	Base year (2015)	2020	2030	2040	2050
Rice area increase (M ha) compared to base year	--	0.97 (36)	1.26 (50)	1.26 (50)	0.91 (35)
Rice production increase (MT) compared to base year	--	2.63 (10)	3.80 (14)	4.15 (14)	3.31 (10)
Projected phasic production requirement over base year (MT)*	35.30	37.00	40.40	43.80	47.20

Note: Value in the parentheses is the percentage computed based on the year 2015. *Source: Kabir *et al.* 2020

Table 8. Research and extension activities for enhancing rice production in unfavourable ecosystems and stress environments under future conditions in Bangladesh.

Unfavourable ecosystem	Action required to improve the prevailing conditions for increased rice production	2021-2030		2031-2040		2041-2050	
		2021-25	2026-30	2031-35	2036-40	2041-45	2046-2050
Salinity	• Characterization of ecosystem (Distribution and severity of soil and water salinity)	Completing		Updating info		Updating info	
	• Variety (Salinity+drought+heat+stagnation tolerant with short duration)	Continue improving					
	• Water management (Source of sweet water, rainwater harvest and management of canals)	Continue improving					
	• Crop management (Ridge and furrow planting, mulching for non-rice crop)	Continue improving					
	• Soil health management (Addition of organic matter, balanced fertilization, gypsum and potash application)	Continue improving					
	• Policy development (Polder management, area demarcation for salt and shrimp farming)	Continue improving					
Submergence	• Characterization of ecosystem (Flooding depth, duration, turbidity, turbulence, dissolve oxygen concentration)	Completing		Updating info		Updating info	
	• Variety (Multiple flood tolerant, drought and stagnation tolerant including photosensitivity)	Continue improving					
	• Specific fertilizer management for quick recovery after de-submergence	Continue improving					
	• Location specific variety adoption and management practices	Continue improving					
Drought	• Characterization of ecosystem (Occurrence, severity and duration, sources of irrigation, rainwater harvest)	Completing		Updating info		Updating info	
	• Variety (Highly drought tolerant, heat tolerant and short duration)	Continue improving					
	• Adjusting planting time to escape drought period	Continue improving					
	• Location specific variety adoption and management practices	Continue improving					

Table 8. Continued.

Unfavourable ecosystem	Action required to improve the prevailing conditions for increased rice production	2021-2030		2031-2040		2041-2050	
		2021-25	2026-30	2031-35	2036-40	2041-45	2046-2050
Haor	• Characterization of ecosystem (Depth of water and suitability DW, FR and enhanced Boro cultivation)	Completing		Updating info		Updating info	
	• Variety (Pureline selection of DW and FR-landrace including drought tolerances at early stage of growth)	Continue improving					
	• Crop management (Fertilizer, weed, pest, rat management and harvesting issues)	Continue improving					
	• System productivity enhancement (Boro + DWR/FR + Fish + Duck) could be most productive system	Continue improving					
Tidal Submergence	• Characterization of ecosystem (Characterizing tidal waves by depth, turbulence and quality of water)	Completing		Updating info		Updating info	
	• Variety (Taller and flexible/tender stem, strong photosensitivity, glossy leaves)	Continue improving					
	• Efficient fertilizer management under tidal water condition	Continue improving					
	• Location specific variety adoption and management practices	Continue improving					
Rainfed Low Land	• Characterization of ecosystem (Flooding depth, duration, stagnation, drought severity)	Completing		Updating info		Updating info	
	• Variety (Submergence, drought, heat and stagnation tolerance including strong photosensitivity)	Continue improving					
	• Crop management (Double transplanting, weed and fertilizer management)	Continue improving					
	• Water management (Special water management like supplemental irrigation)	Continue improving					
Upland	• Characterization of ecosystem (Plough pan/hardpan, suitability for water saving rice)	Completing		Updating info		Updating info	
	• Variety (Deep root system, water saving, drought and heat tolerant, short duration, and perennial type)	Continue improving					

Table 8. Continued.

Unfavourable ecosystem	Action required to improve the prevailing conditions for increased rice production	2021-2030		2031-2040		2041-2050	
		2021-25	2026-30	2031-35	2036-40	2041-45	2046-2050
	• Crop management (Water saving technique-mulching, weed and pest management)	Continue improving					
Charland	• Characterization of ecosystem (Suitability of rice + non-rice crop cultivation, source of irrigation water)	Completing		Updating info		Updating info	
	• Variety (Short duration, drought and heat tolerant)	Continue improving					
	• Crop management (Improvement of soil health and productivity)	Continue improving					
Low temperature	• Characterization of ecosystem (Demarcation of low temperature regime, severity and duration of low temperature stress)	Completing		Updating info		Updating info	
	• Variety (Low temp tolerant for seedling & reproductive stage)	Continue improving					
	• Adjustment of planting to escape low temperature effect in combination with yield target	Continue improving					
	• Seedling raising under high temperature condition to escape low temperature effect	Continue improving					
High temperature	• Characterization of ecosystem (Delineation of high temperature regime, severity and duration of high temp.)	Completing		Updating info		Updating info	
	• Variety (Drought and heat tolerant with Early Morning Flowering to escape heat period during flowering)	Continue improving					
	• Efficient water management to mitigate heat and drought effects	Continue improving					
For all ecosystems	• Up-scaling activities: --Site characterization -- Set demonstration						
	• Set large-scale/mass demonstration						
	• Developed extension linkage						

'info' denoted for information

CONCLUSION

BR23, BRRI dhan40, BRRI dhan41, BRRI dhan47, BRRI dhan53, BRRI dhan54, BRRI dhan61, BRRI dhan67, BRRI dhan73, BRRI dhan78, BRRI dhan97, BRRI dhan99, BINA dhan8 and BINA dhan10 are resilient to salinity. Besides, BRRI dhan56, BRRI dhan57, BRRI dhan66, BRRI dhan71, and BRRI dhan83 are resilient to drought, and BRRI dhan51, BRRI dhan52, BRRI dhan79, BINA dhan11, and BINA dhan12 are tolerant to submergence. The BR18, BRRI dhan36, BRRI dhan67, and BRRI dhan69 are to some-extent cold resilient. About 1.26 MT, 3.45 MT, and 9.18 MT rice production may increase subject to improve agronomic practice and adoption of stress-tolerant rice cultivars in the 0.37 Mha, 1.08 Mha, 2.94 Mha of the salinity, submergence, and drought ecosystems, respectively. Resulting from that 13.89 MT of rice will be added to the national rice basket in 2050. The policy supports are needed for rapid dissemination of the stress-tolerant cultivars in unfavourable ecosystems and development of more stress-tolerant rice cultivars and management practices for future conditions.

RECOMMENDATIONS

- The extension supports need to be strengthened for disseminating currently available specific abiotic and biotic stress-tolerant rice cultivars to the respective stress-prone ecosystems to enhance rice production in the country to achieve SDGs.
- Farmers' access to higher yield potential and further stress-tolerant (multi stress-tolerant) cultivars for saline, submergence, and drought-prone ecosystem needs to be developed and disseminated to achieve the SDGs and for meeting the increased demand of the growing population by 2050.
- Climate-smart agronomic and pest management technologies in the saline, submergence, drought, and cold-prone ecosystems need to be developed and disseminated.
- Varieties with higher yield potential and up to four weeks and recurrent submergence tolerance at the vegetative phase, and drought at the reproductive phase need to be developed and disseminated to the submergence ecosystem to reduce the unexpected yield loss. Besides, agronomic management needs to be improved to achieve the expected yield of the ecosystem.
- Farmer's access to fresh-water for irrigation in the saline and non-saline ecosystem needs to be improved through re-excavation of canals and developing farm-friendly canal water management for achieving SDGs.
- Rice varieties and agronomic practices need to be developed for flash flood submergence-prone ecosystem considering the gravity of floods, including water depth and quality (muddy or clear), frequency of occurrence, and length.
- The over-extraction of underground waterneeds to be reduced through capitalizing the rainwater by adjusting cropping seasons and storing the rainwater in the reservoirs in the drought-prone ecosystem. Besides, the adoption of improved irrigation water management for cropping might reduce the excessive stress of groundwater aquifer.
- For the upland environment, higher yield potential and drought-tolerant Aus rice cultivars need to be developed for enhancing productivity and farm income. The policy supports are needed for enhancing rice area and productivity through improving nutrient management and agronomic practices in the ecosystem.
- For Charland, rice variety needs to be identified and developed based on soil types, drought severity, and irrigation water

availability to enhance rice production in the ecosystem.

- The development of higher yield potential short duration and cold-tolerant (at reproductive phase) rice cultivars are required to overcome flash floods and cold stress in the Haor ecosystem. Besides, the development of an early-warning system about flash floods at the reproductive phase of Boro rice in the ecosystem might reduce unexpected crop loss. Similarly, rice cultivar tolerance to cold at seedling and reproductive phase need to be developed for the north-east and west region of the country. Shifting transplanting time of Boro rice to early and delaying the short duration T. Aman rice varieties might help to reduce unexpected yield plenty due to heat stress. Besides, the development and dissemination of early morning flowering potential rice varieties might also reduce unexpected yield loss across seasons and ecosystems.

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AUTHORS' CONTRIBUTION

MSR generated idea; AKMSI, MARS and MAAM coordinated the research; MSR and MMH developed methodology; MSR, MMH, MJK, MUS and MSK provided scientific insights; MSR gathered data, carried out analysis and synthesis; MSR did the writings for all versions of the manuscript; MJK, MARS, MAAM and MUS performed critical review and editing; All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

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Grain Quality Research of Rice for Ensuring Nutritional Food Security

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ABSTRACT

Per capita rice consumption in Bangladesh is in a decreasing trend. Considering the constant loss of per capita daily dietary energy @ 0.028% year^{-1}, nutrition-based prediction of daily dietary energy intake (kcal) may be reduced to 2201 and 2188 kcal for our population by 2030 and 2050, respectively. We are optimistic that consuming per capita rice consumption of 365 g and 363 g (dry wt. basis) in 2030 and 2050, respectively will help to attain the current trends of 59.0% of Calorie intake from rice only. Appropriate amount of rice intake including incorporating rice-based products in our daily diet, we will able to attain daily required dietary allowance and combination of both may ensure nutritional security along with food security in Bangladesh in a way to effective utilization of the rice grain. Rice is nutraceutically enriched because of the presence of phenolic compounds, flavonoids and antioxidants. Research thrust of BRRI is to focus on releasing nutraceutically enriched HYVs such as high zinc, high iron, beta carotene (A Vit A precursor) enriched antioxidant rice etc. Gluten free rice-based bakery products have potential to get popularize in Bangladeshi population with ensuring high nutritional value and effective management of controlling non-communicable diseases since lesser amount of rice carbohydrates are being utilized in formulating products such as rice biscuit, rice cake etc. BRRI has formulated gluten free rice-based energy dense product specially rice biscuit (ED 5.15) could be extended as a potential nutritionally balanced dry food application in malnutrition mitigation programme, school feeding nutritional programme and humanitarian relief operation replacing current wheat-based products.

Key words: Nutraceutical, malnutrition mitigation, gluten free rice-based bakery products. energy dense rice biscuit.

INTRODUCTION

The nutrient content of rice varies depending on rice soil, and the conditions they grow. A better understanding of the intrinsic factors that contribute to the overall rice grain quality will set the foundation for developing new breeding and selection strategies for combining high grain quality, with higher yield and nutritional value. Rice producing countries have the potential to generate higher export revenues by meeting the ever-increasing global demand for high-quality rice specially nutraceutical enriched premium quality rice. Bangladesh can not be an exception in this regard.

The malnutrition scenario of the Bangladeshi population

Humans need at least 49 different types of nutrients for their regular development and the majority of the required nutrients are supplied by cereals, particularly rice due to its staple role (Welch, 2004). Minerals play numerous beneficial roles due to the effect on both plant and human metabolism. The deficiencies or an insufficient intake of nutrients lead to several dysfunctions and diseases in humans, such as anemia for iron, stunting for zinc, and osteoporosis for calcium which are most prevalent in developing countries (Welch *et al.*, 1999). Malnutrition in Bangladesh is alarmingly high since approximately 36.2% children of under five years of age are stunted, 15% are wasted and 33% are underweight (Sunanda and Jahida, 2017). Both malnutrition and poverty hamper access to education especially the ability to learn. One in every five preschool or school-aged children suffers from vitamin A deficiency in Bangladesh. Also, 33% of preschool children

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are anemic, 9% of women have folate deficiency and 22% of women are suffering from Vit-B_{12} deficiency in our population. According to the National Micronutrients Survey 2011-2012, Bangladesh has a frequency of zinc deficiency is about 44.6% amongst preschool-age children and 57.3% amongst non-pregnant non-lactating women.

Nutrient loss negatively correlates with the degree of milling

The principle of rice milling is the removal of the husk (husking) followed by the rice bran (polishing), which gives us the edible portion (endosperm) of rice grain. Certain nutrients like fats, vitamins, proteins, and minerals are found in good concentration in germ and outer layers of endosperm i.e. bran portion of kernels. In 2007, Lamberts *et al.,* showed that about 84.2% of kernel proteins are concentrated in outer endosperm, and upon milling further the concentration of proteins decreases. They found that 61% of most of the minerals are present in the bran fraction of the kernels whereas the core of the endosperm fraction mainly consists of starch (84.6%) in the kernels. Milling is a phenomenon of wear that involves removing material from a solid surface either by mechanical action or by combinations of various actions such as rolling, impacting, or sliding. Commercial milling is a process consisting of various stages where firstly paddy or rough rice goes through the dehusking process and then the outer brown bran layer is removed during the whitening process. In the final step, the adhering bran is completely removed from the grain surface and is known as polishing. The quality of milled rice is depicted by two important parameters i.e., the whiteness of the kernel and yield of head rice (HRY). Rice can be milled by two methods i.e., abrasion milling and friction milling. When the rice grain is made to revolve inside a milling chamber, then the grain which gets in touch with the emery surface experiences abrasion type of milling while grain which rubs against each other experiences adhesive type of wear. In rice polishing, generally, a combination of both types of wear is used, as, no pure form of milling has yet been discovered. Rubber rolls were determined to be most suitable for laboratory scale milling operations as these increased the dehusking percentage but decreased the breakage of rice kernels. During milling operations, these nutrients are removed thus reducing the nutritive value of starch. The degree of milling (DOM) affects the concentration of nutrients. The proximate composition depends upon the degree to which the bran has been removed from the kernel surface. The rice subjected to lower DOM could lead to more nutrition which can assure better health of the consumers (Puri, 2014). The speed of the impeller cannot be taken as a sole criterion for optimization of impeller husker performance, as it depends on the size and shape of rice kernels also (Puri, 2014). This could be judged by a low husked ratio even if the impeller speed was at its optimum. The quality of rice milling is affected by the moisture content of paddy as well as the rotor speed of the whitener. Various experiments were performed using different cultivars and different types of milling material such as plywood, iron sheet, rubber, glass, and fiberglass. Milling in rubber roll huller was found to be the most effective for paddy but least for milled rice. In 2010, Firouzi *et al.*, evaluated the performance of perforated screen size and blade rotor clearance for whitening of rice grain. During the milling process, the losses of minerals reached up to 84.7%. Fukai and Godwin,(2007) milled brown rice cultivars and measured loss in iron content. The iron content of 25-84% was lost during the milling process.

Functional properties of rice

Rice is an important source of energy, hypoallergenic, easily digested, providing protein with higher nutritional quality, and has versatile functional nutraceutical properties. Rice has an important role in the relation between diet and health. several compounds with antioxidant activity have been identified in rice, including phenolic compounds, tocopherols, tocotrienols, and γ-oryzanol (Iqbal *et al.,* 2005). The phenolic compounds are mainly associated with the pericarp in rice; hence, the milling process reduces the concentration of these compounds in the grain. Besides, grains with darker pericarp colour, such as red and black rice, contain higher amounts of polyphenols (Tian *et al.,* 2004; Zhou *et al.,* 2004). The concentration of total phenolics in the grain has been positively associated with the antioxidant activity (Itani *et al.,* 2002; Zhang *et al.,* 2006). Therefore, it reduces oxidative stress (Ling *et al.,* 2001), cancer (Hudson *et al.,* 2000; Hu *et al.,* 2003), blood lipids and related diseases, and hence prevents cardiovascular problems (Ling *et al*., 2001), and diabetes complications (Morimitsu *et al*., 2002; Yawadio *et al*., 2007).

Water soluble vitamins in rice

People intake thiamin Vit-B_1 for conditions related to low levels of thiamin (thiamin deficiency syndromes), including beriberi, inflammation of the nerves (neuritis) associated with pellagra, or pregnancy. Thiamin is also used for digestive problems including poor appetite, ulcerative colitis, diabetic pain, heart disease, alcoholism, aging, vision problems such as cataracts, glaucoma, motion sickness, improving athletic performance, preventing cervical cancer and progression of kidney disease in patients with type-2 diabetes, AIDS and boosting the immune system. Thiamin functions as a coenzyme in the metabolism of carbohydrates and branched-chain amino acids. Recommended Dietary Allowance (RDA) for adults is 1.2 and 1.1 mg day^{-1} for men and women, respectively. Riboflavin functions as a co-enzyme in numerous redox reactions. The RDA for riboflavin for adults is 1.3 and 1.1 mg day^{-1} for men and women (Institute of Medicine, 1998), respectively.

Gluten-free rice-based bakery food products

Food intolerance became an important public health concern, and the identification of effective strategies for prevention is obligatory. There is an increasing incidence of coeliac disease or other allergic reactions/intolerances to gluten. This intolerance can be at any age, from early childhood to the elderly. Since rice does not have gluten protein naturally, it has advantages to prepare rice-based bakery products over wheat-based products**.** Bangladesh Rice Research Institute **(**BRRI) has formulated several gluten-free rice-based products such as rice biscuit, cake, bread and bun, and gluten-free rice-based processed food items have the potential scope in Bangladesh specially for malnutrition mitigation approach, school feeding nutrition programme, disaster management programme, etc. In this regard, BRRI has formulated energy-dense nutraceutically enriched rice-based bakery food formulation especially biscuits having energy density ranges from ED 5.0-5.5 per 100 g serving. Rice-based balanced and nutritious food intake might reduce rice consumption from the current rate of 367 g capita^{-1} day^{-1} to 363 g capita^{-1} day^{-1} or lesser for the Bangladeshi population. Since floating urban street children are classified as the most vulnerable group in Bangladeshi population so, nutraceutically enriched rice-based bakery food products might play a role in shifting malnutrition status in this regard. In addition, in quest to attain the required daily dietary allowance on scale of average of 2000 kcal, rice-based energy-dense food might assist as a supplementary diet and it will be helpful to attain the SDG goal for hunger-free and sustain food security in Bangladesh in a way to properly and effectively utilizing the rice grain. Kabir *et al.,* (2020) has also emphasized the established value of production for ensuring the rice productivity double.

In Bangladesh, rice is synonymous to food and has been the customary source of carbohydrates and proteins since the ancient days. BRRI has developed 106 HYVs including both inbred and hybrid. At present, total clean rice production is about 34.9 MT which fulfills the domestic requirement to feed more than 168 million populations. So, it is high time to focus our grain quality and nutrition research towards grain nutraceutical properties especially mineral profiling, phytate estimation, antioxidant profiling, volatile compounds including aroma quantization, low glycemic content, water, fat-soluble vitamin profiling, etc. to reveal its ability to combat with non-communicable diseases (NCD) especially cancer, cardiovascular disease, diabetes, and obesity.

With the above background, this article undertook three specific objectives in relation to rice grain quality in Bangladesh: (i) presentation of dietary energy changing status, (ii) highlighting the scenarios of nutraceutical rice research activities at BRRI, and (iii) developing and mapping the action plan for three decades on improving nutraceutically enriched rice grain quality.

METHODOLOGY

A total of 72 high yielding varieties (HYV) including 68 inbred and four hybrid rice were surveyed for Glycemic Index (GI) screening in vivo experiment (Shozib *et al.,* 2017a) rat model and GI value was measured by AUC (Area under the curve) method (Haffner, 1986; slightly modified by both Psyrogiannis, 2003 and Keh, 2004). Sixty-eight BRRI HYVs were analyzed for mineral profiling of Zn, Fe, Ca, and P elements by standard AOAC methods (AOAC, 1995) for AAS (Atomic absorption spectrophotometer), and 35 BRRI developed HYVs were analyzed for water-soluble vitamins such as thiamine and riboflavin (Shozib *et al.,*2017b; Shozib *et al.,*2018a) by HPLC methods mentioned in ASEAN Manual of Food Analysis (Prapasri *et al.,* 2011). Physicochemical parameters were measured following IRRI evaluation standard SES (IRRI, 2013). Antioxidant properties such as Total Phenolic Content (TPC, mg GAE g^{-1} dry weight), Total antioxidant activity (TAC, AAE g^{-1} dry weight Assay, Ferric ion reducing antioxidant power assay (FRAP, AAE g^{-1} dry weight) and DPPH radical scavenging activity of rice were measured by Singleton *et al.*, (1999), phospho-molybdenum assay by Prieto (1999) and Oyaizu (1986) by 1, 1-dipheyl-2-picryl-hydrazyl (DPPH) using the method described by Oktay *et al.,*(2003) respectively. The water-soluble vitamins are extracted from the rice powder by acid hydrolysis followed by enzymatic hydrolysis. Thiamin and riboflavin in rice were measured by HPLC method (ASEAN Manual of Food Analysis).

In the baseline survey (Saima *et al.,*2020) on dietary intake of street children our target population was both boys and girls of 4-12 years old street children. We have interviewed 384 street children from above mentioned 20 hot spots in the capital city of Dhaka. Using Cochran Equation, we found the sample size 384.

$$Sample\ size = \frac{Z^2\ P\ (1-P)}{E^2}$$

The value of Z is found in statistical tables which contains the area under the normal curve. Z = 1.96 for 95% level of confidence. P is the estimated proportion of an attribute that is present in the population.

E^2 is the desired level of precision.

$$Sample\ size = \frac{Z^2\ P\ (1-P)}{E^2} = \frac{1.96^2\ \times 0.5\ \times (1-\ 0.5)}{0.05^2} = 384.16 \approx 384$$

Rice-based bakery products were formulated according to the general guideline of Biscuit and cake of BSTI, Bangladesh. Gluten-free energy-dense rice biscuit (EDRB) and energy-dense rice cake (EDRC) were also formulated.

Per capita rice consumption (kcal) projection was made using continuous exponential growth model $y = a(1 + r)^x$. Here y = per capita rice consumption in kcal, r = growth rate, a = initial value and x = time interval. Per capita rice consumption data of BBS-HIES 2016 was selected for the initial value. Observed kcal data of BBS were used as 2244, 2240, 2238, 2318, and 2210 for 1995, 2000, 2005, 2010, and 2016 respectively to calculate the growth rate. We have predicted the daily dietary energy intake projection for 2050 considering all the food components contribution into account.

RESULTS AND DISCUSSION

Daily dietary energy intake projection

Since rice is the major dietary energy source among the cereal crops for our population, so rice should be nutraceutically enriched in terms of antioxidants, minerals, having low glycemic and higher protein, etc. In order to attain SDG goals on safe and nutritional food, newly released HYVs will have to be aligned with special nutraceutical properties such as antioxidants enriched and high content of minerals especially zinc (>27.50 ppm), iron (>10.00 ppm), and vitamin A (>8.64 ppm) etc. Reviewing the per capita per day Calorie (kcal) data from the year 1995 to 2016, we observed that these years had declining trends of 0.028% year^{-1}. Considering the constant loss of per capita daily dietary energy @ 0.028% year^{-1}, nutrition-based prediction of daily dietary energy intake (kcal) might be reduced to 2201 and 2188 kcal for our population by 2030 and 2050, respectively (Table 1 and Fig. 1). We are hopeful that consuming per capita rice consumption of 365 g and 363 g (dry wt. basis) in 2030 and 2050, respectively will help to attain the current trends of 59.0% of Calorie (kcal) intake from rice only.

Energy plays a vital role in our daily activities. Fruits and vegetables are treated as an energy booster and provide a diversified, flavoured, colourful, tasty, low caloric, and protective, micronutrient rich diet. A healthy diet contains fruits, vegetables, legumes (e.g. lentils, beans), nuts, and whole grains (WHO, 2020). The total per capita food intake (g) of the Bangladeshi population decreased from 2010 to 2016 by 2.5%. Per capita rice and wheat (g) intakes decreased by 11.77% and 62.32% from 2010 to 2016 but simultaneously per capita pulses, vegetables, fish, meat, and egg intake (g) increased by 9.09, 0.73, 26.65, 29.99, and 87.31%, respectively for the same period of time (HIES, 2016). The overall calorie intake per capita per day has decreased to 2210 kcal in 2016 from 2308 kcal in 2010 (a decrease of 4.23%). This is may be due to a substantial decrease in rice consumption in 2016 compared to 2010 (HIES, 2016).

Table 1. Prediction of per capita rice consumption in Bangladesh.

Year	Source	Energy intake (kcal person^{-1} day^{-1})	Rice intake (g person^{-1} day^{-1})	Energy from rice (kcal)	Calorie (%)	Rice intake (kg person^{-1} year^{-1})
2016	HIES, BBS	2210	367	1307	59	134
2020	Projected*	2207	366	1302	59	134
2025	Projected*	2204	365	1300	59	133
2030	Projected*	2201	365	1299	59	133
2035	Projected*	2198	364	1297	59	133
2040	Projected*	2195	364	1295	59	133
2045	Projected*	2192	363	1293	59	133
2050	Projected*	2188	363	1291	59	132

*Projection was made by considering the constant loss of per capita daily dietary energy @ 0.028% year^{-1} using a continuous exponential growth model and 100 g serving of raw rice generates approximately 356 kcal of energy. HIES and BBS denotes Household Income and Expenditure Survey and Bangladesh Bureau of Statistics.

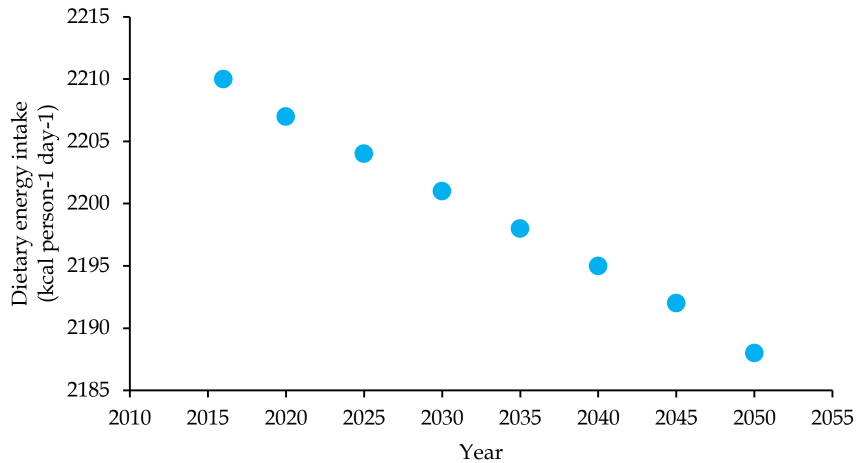

Fig. 1. Predicted per capita dietary energy intake (kcal) by 2050 in Bangladesh.

Daily protein intake from rice

The DRI (Dietary Reference Intake) is 0.8 grams protein per kilogram body weight (Gabrielle *et al.*, 2008). For the average sedentary women (57.5 kg) and men (70 kg), 46 and 56 grams of protein intake per day is required respectively. Approximately 45.87% of the daily recommended protein comes from the current rate of rice consumption (367 g provides 28.9 g of protein) and it will further be continuing to get 28.6 g protein from 363 g per capita rice intake in 2050 as projected (Table 2). Currently, we are getting an average of 7.90% rice protein from our well adopted BRRI HYVs and expected to increase rice protein up to 9.0 and 10.0% through our newly released HYVs, which will enable to increase 12.22% and 26.58% more protein supplementation from rice only in our food table by 2030 and 2050 respectively (Table 2).

Desire characteristics of future HYV

New HYVs should also be considered for specific physicochemical traits such as high apparent amylose content (>25% AAC) with soft gel consistency (Soft GC, >61-100 mm), translucent (Tr) and long slender to medium slender size and shape grain, etc. Based on the consumer's preference for non-sticky soft rice, these types of rice may be popular in our population in the coming days. The specific grain quality characteristics such as whiteness, broken rice, shape, apparent amylose content

Table 2. Per capita protein intake per day from plant source (Rice).

Year	Source	Per capita rice consumption (g $person^{-1}$ day^{-1})	Protein (g) from plant source (HYVs having ~7.9% protein)	Protein (g) plant source (HYVs having 9% protein)	Protein (g) plant source (HYVs having 10% protein)	Increased (%)
2016	HIES, BBS	367	28.993	-	-	-
2030	Projected	365	28.835	32.85	-	12.22
2050	Projected	363	28.677	-	36.3	26.58

Average 70 kg body wt. human requires 56 g protein (including both vegetable and animal sources) per day (0.8 g kg^{-1} body wt.). HYV denotes high yielding variety.

(AAC%), aroma, cooking quality such as gel consistency (GC), and chalkiness influenced the consumers' and producers' preference. Nutraceutically enriched black rice, antioxidant, low GI, Zn, Fe, and Vitamin A enriched advance breeding materials should be screened to get the above mentioned desired grain quality and nutritional characteristics for newly superior HYVs. Estimation of the molar ratio of Phytate (PA) to minerals is a very important parameter for understanding the bioavailability of minerals since low phytate containing rice is desirable for plant breeders (Shozib *et al*., 2017b).

Nutraceutical rice varieties in Bangladesh

BRRI has identified a number of nutraceutical enriched HYVs such as three low glycemic index rice namely BR16 (GI 52.4), BRRI dhan46 (GI 53.1), BRRI dhan69 (GI 54.9), eight Zn enriched HYVs namely BRRI dhan42 (27.12 ppm), BRRI dhan43 (27.17 ppm) for Aus season, BRRI dhan62 (19.0 ppm), BRRI dhan72 (22.0 ppm) for Aman season, BRRI dhan64 (24.0 ppm), BRRI dhan74 (24.40 ppm), BRRI dhan84 (27.60 ppm), BRRI dhan100 (25.7 ppm) for Boro season, two thiamin (Vit-B_1) and riboflavin (VitB_2) enriched BRRI dhan42, BRRI dhan43, four antioxidant-enriched HYVs namely BRRI dhan84 (TPC 37.74 mg GAE), BR5 (TPC 25.30 mg GAE), BRRI dhan88 (TPC 23.07 mg GAE) and one GABA (gamma aminobutyric acid) enriched pre-germinated brown rice namely BRRI dhan31 (Shozib *et al*., 2017a; Shozib *et al*., 2017b; Shozib *et al*., 2018a; Siddiquee *et al*., 2017). For BRRI dhan29 containing the GR2E Golden Rice trait, concentrations of the b-carotene equivalents (BCEs) are approximately 12.0 $\mu g g^{-1}$ (ppm) (Donald, 2018). Besides these 17 nutraceuticals enriched HYVs, BRRI is conducting diversified research activities with anthocyanin enriched black rice in both animal and human cell lines to combat non-communicable diseases such as cancer, diabetes, and hypertension.

Over polishing (≥10%) effect on nutritional loss

In 2007, Lamberts *et al*., reported that the mineral content is the highest in the bran (61.0%), followed by outer endosperm (23.7%), core endosperm (11.6%), and the lowest in the middle endosperm (3.7%). Proteins, minerals, and starch were not uniformly distributed in the brown rice kernel. Bran (DOM<9%) contained most of the minerals (61.0%). Shozib *et al*., (2018a) found variation in Zn content with increasing polishing time from 80 seconds to 180 seconds at DOM on a laboratory scale. Rice samples were dehusked by Satake Rice mill, followed by 80, 100, 120, 140, 160, and 180 second polishing in a Grainman rice polisher (USA) to get 8.5, 9.0, 9.5, 9.9, 10.3, and 10.6% polished rice (clean rice or milled rice) respectively as an average scale for 5 HYVs such as BR25, BRRI dhan36, BRRI dhan42, BRRI dhan43 and BRRI dhan64 in the mineral analysis. At 80 seconds of polishing, DOM varied ranges from 6.19 to 10.46% for five selected HYVs whose grain size and shape are also varied from small and medium grain, long and slender grain, medium, and bold grain, etc. Zn content of BR25, BRRI dhan36, BRRI dhan42, BRRI dhan43, and BRRI dhan64 were 24.70, 23.60, 27.12, 27.17, and 24.46 ppm respectively at 80 seconds of polishing. Zn content of BR25, BRRI dhan36, BRRI dhan42, BRRI dhan43, and BRRI dhan64 was 21.30, 20.43, 24.21, 23.90, and 22.10 ppm respectively at 140 seconds of polishing where DOM varied ranges from 7.78 to 11.28%. Finally, Zn content of BR25, BRRI dhan36, BRRI dhan42, BRRI dhan43, and BRRI dhan64 were 18.21, 17.34, 20.43, 27.17, and 20.10 ppm respectively at 180 seconds of polishing where DOM varied ranges from 10.15 to 12.02%. Authors have demonstrated how Zn content and DOM of five different BRRI HYVs significantly varied at different polishing time ranges from 80 seconds to 180 seconds considering grain size and shape into account. For citation, in the commercial milling process a nutraceutically enriched BRRI dhan42 can lose a maximum up to 24.7% of Zn at 18.4% degree of milling (DOM). The more we will increase the degree of milling the more nutrient we will lose. In this regard, 1st pass which means 7.4%, DOM is enough to get 27.1 ppm of Zn from BRRI dhan42. On the other hand, 11% extra milling will produce whitening starch compounds only but fewer or trace amounts of fiber, ash, and fat which will cause health hazard directly.

Since over-polishing (>10%) of rice does not possess much nutrients, fiber, vitamins, and minerals so, it will not be able to bring any health benefit rather it is a threat of some non-communicable diseases. We have to fix rice milling ≤10% DOM through any interventions either from the government and NGOs or both so that we will be able to get the maximum benefit of nutraceutical properties of rice indeed. Escaping an extra 10% DOM loss will help to achieve productivity double in quantity. Consuming a lesser degree of milling rice will not only assist in the productivity doubling process but it will qualitatively improve our nutritional status as well. Recently released BRRI HYV's grain types are recorded as long slender, long bold or medium slender such as BRRI dhan80, BRRI dhan81, BRRI dhan84, BRRI dhan85, BRRI dhan86, BRRI dhan87, BRRI dhan88, BRRI dhan89. So, these HYVs need not to be over-polished.

Table 3. Loss percentage of Zn content in BRRI dhan42 during commercial milling (unpublished data of GQN Division, BRRI, 2019).

Pass	DOM (%)	Zn (ppm)	Zn loss (%)
1st	7.4	27.1	-
2nd	10.9	25.3	6.9
3rd	13.9	22.6	16.9
4th	16.4	21.8	19.6
5th	18.4	20.4	24.7

Note: DOM denote degree of milling; ppm indicate parts per million

Aspects of rice-based bakery products in Bangladesh

BRRI scientists have formulated nutraceutically enriched rice-based popular bakery food products such as rice biscuits, rice cakes, rice bread, etc. These rice-based bakery products are gluten-free and consist of high protein, minerals (Zn Fe, Ca, and P), antioxidants, vitamins such as thiamin and riboflavin, etc. Scientists also formulated energy-dense rice cookies or biscuits (Energy Density; ED 5.15, 100 g serving provides 515 kcal, high protein >10% and high-fat content of 25%) which are low cost, safe, and nutritionally balanced (Shozib, 2018b). Rice-based products require lesser amount of carbohydrates than we have usually taken as cooked rice for a single meal. For example, 100 g serving rice-based food items required 50 g carbohydrate to generate 500 kcal and on the other hand 125 g raw rice required to generate the same quantity of energy by consuming cooked rice for a single meal (1.0 g carbohydrate generate 4.0 kcal energy).

Rice-based products are supposed to be formulated in an ideal proportion of carbohydrate, fat, protein ratio as 50:30:20. So there is a huge scope in increasing the average income of small-scale food producers especially learned farmers and local bakery owners in adopting nutraceutically enriched rice production.

Rice-based bakery products can potentially be used to minimize malnutrition of the most vulnerable portion of our population especially street children. Since street children are the most vulnerable group of population coming to fight to gild the streets for their habitual abode and livelihood drifted into a nomadic life. These children are generally malnourished due to their deprivation of health care and improved nutrition. In 2021, Saima *et al.*, conducted a baseline survey on street children of the capital city, Dhaka on both boys and girls of 4-12 years. A total of 384 street children were subjected to study a baseline survey. The sample size was fixed by addressing Cochran equation. Among the respondents 63% were male and 37% were female from street children population of 384. Survey took place at 20 different hot spots covering both garts of Dhaka city north and south. We have observed the recommended dietary intake per day from 4 years to 12 years old male boys and found 27 to 59% deficiency in our male population samples of 243. Similarly, we also observed the recommended dietary intake per day from four years to 12 years old female girls and found 28 to 56% deficiency in our female population samples of 141. Since our energy dense rice cake (EDRC) has a potential of providing 500 kcal energy per 100 g serving so, we could predict that incorporating our improved rice-based product once a day along with their daily regular intake, it will able to mitigate nutritional gap by 64 to 100% for street boys and noticeably 70 to 100% for girls. We have prepared energy dense rice biscuit (EDRB, 3.6% moisture, 515 kcal per 100 g of serving) and energy dense rice cake (EDRC, 5.0% moisture, 500 kcal per 100 g of serving). EDRC was found prepared than EDRB in impact study when the respondents were given choice of rice-based bakery items intake for four months long period. Finally, a total of 32 respondents took part in a four months period impact study on EDRC from street children population. All anthropometric and biochemical data such as CBC (Complete Blood Count), Hemoglobin, CRP, Prealbumin etc. were collected at both the starting (Day 0) and the end time (Day 120) of the impact survey of selected 32 respondents. Respondents were given 100g serving of EDRC every day (Rice cake) to 32 street children samples for 4 months period along with their normal food intake. Our data revealed that malnutrition related parameters specially CRP (decreased) and Prealbumin (Increased) are significantly improved during four months supplementary intake of extra 500 kcal per 100 g serving of EDRC in tested street children's samples which resemble the possible impact of EDRC on street children. Rice-based bakery products specially EDRB and EDRC can potentially be used in school feeding nutritional programme and disaster management in Bangladesh.

Table 4. Baseline survey on daily dietary intake of street children (age 4-12) for boys.

	Age	RDI In kcal	Observed data in kcal	Observed data ranges	RDI % intake	Gap in kcal	Gap % of RDI	EDRB kcal per 100 g serving	EDRB provide RDI %	Gap % of RDI % Remain	Predicted gap minimization of RDI %
Male N=243	4 (n=13)	1303	955	600-1100	73	348	27	515	40	-13	100
	5 (n=11)	1362	865	630-1210	63	497	37	515	38	-1	100
	6 (n=14)	1403	852	670-1180	61	551	39	515	37	3	97
	7 (n=21)	1507	994	720-1187	66	513	34	515	34	0	100
	8 (n=20)	1624	919	620-1170	57	705	43	515	32	12	88
	9 (n=35)	1750	865	620-1250	49	885	51	515	29	21	79
	10 (n=32)	1890	877	670-1300	46	1013	54	515	27	26	74
	11 (n=40)	2038	866	620-1400	42	1172	58	515	25	32	68
	12 (n=57)	2200	893	650-1280	41	1307	59	515	23	36	64

EDRB: Energy dense rice biscuit; ED: Energy Density: RDI: Recommended dietary intake.

Table 5. Baseline survey on daily dietary intake of street children (age 4-12) for girls.

	Age	RDI In kcal	Observed data in kcal	Observed data ranges	RDI % intake	Gap in kcal	Gap % of RDI	EDRB kcal per 100 g serving	EDRB provide RDI %	Gap % of RDI % Remain	Predicted gap minimization of RDI %
Female N=141	4 (n=12)	1244	898	625-1110	72	346	28	515	41	-14	100
	5 (n=19)	1202	850	700-1300	71	352	29	515	43	-14	100
	6 (n=11)	1300	769	658-1020	59	531	41	515	40	1	99
	7 (n=28)	1403	884	620-1180	63	519	37	515	37	0	100
	8 (n=11)	1502	1002	820-1210	67	500	33	515	34	-1	100
	9 (n=13)	1638	767	672- 970	47	871	53	515	31	22	78
	10 (n=15)	1777	931	670-1170	52	846	48	515	29	19	81
	11 (n=21)	1942	863	650-1025	44	1079	56	515	27	29	71
	12 (n=11)	2070	930	850-1270	45	1140	55	515	25	30	70

EDRB: Energy dense rice biscuit; ED: Energy Density: RDI: Recommended dietary intake

ACTION Plan (2021-2050)

To fulfill the SDG goal on nutritional security, Grain Quality and Nutrition (GQN) Division of BRRI should follow the proposed action plan (Table 6) through 10 year period of interval (Table 7) from 2020 to 2050. A total of 10,500 (estimated) genebank entities of BRRI including advanced breeding lines, BRRI released HYVs and local germplasms will be evaluated for physicochemical, nutraceutical properties during these three decades from 2021-2050. The action mapping plan is divided into two separate themes such as research and development, and dissemination. Themes are divided into three phases such as primary, secondary, and tertiary phases. Further, it is segmented in several progresses such as characterization, baseline survey, product formulation, sensory evaluation, training, and dissemination.

In the progress of characterization of a primary phase several activities will be taken to fully characterize germplasm such as physicochemical (Physical and Chemical properties), nutraceutical (Nutrition and Medicinal properties), minerals profiling (Macro and Micronutrients), heavy metal profiling (As, Cd, Pb, Ni, Cr), aroma profiling, fatty acid profiling (Rice bran, Rice Bran Oil), amino acid profiling, prebiotics production (Rice straw and Rice Bran), vitamin profiling (Water- and fat-soluble vitamins), antioxidant profiling, and proximate analysis.

The baseline survey will be followed by rice grain characterization and it will come in the second phase including several activities such as a baseline survey on rice grain preferences of farmers, millers, and consumers and baseline survey on rice-based products of manufacturers and consumers. Few superior rice cultivars or HYVs will be selected for three following decades based on consumers' preference through the above mentioned activities (Table 6).

Product formulation will come to 3rd progress in tertiary phase with several actions such as product profiling of quality rice grain, rice-based nutrient dense products formulation (Value added rice-based products), multiple rice-based food products for disease management, the residual effect of herbicides and pesticides of rice grain and rice-based products, proximate analysis of rice-based products, energy estimation and quality analysis of rice-based food products. The sensory evaluation will be followed by product formulation in tertiary phases which includes several activities such as quality rice grain selection and rice-based nutrient dense products formulation (Value added rice-based products). Dissemination will be adopted at the tertiary phase including two stages such as training and demonstration with several actions such as training for food manufacturer, rice miller and RBO miller and demonstration in bakery and food industries (Table 7).

Table 6. Action plan for ensuring safe rice consumption with superior grain quality and nutrition.

Action title	Ensuring safe rice consumption with superior grain quality and nutrition		
Theme	Phase	Progress	Activities
Research and Development	Primary	Characterization	1. Physicochemical (Physical and Chemical properties) 2. Nutraceutical (Nutrition and Medicinal properties) 3. Minerals profiling (Macro and Micronutrients) 4. Heavy metal profiling (As, Cd, Pb, Ni, Cr). 5. Aroma profiling 6. Fatty acid profiling (Rice bran, Rice bran oil) 7. Amino acid profiling 8. Prebiotics (Rice straw and Rice bran) 9. Vitamin Profiling (Water- and fat soluble vitamins) 10. Antioxidant profiling 11. Proximate analysis
	Secondary	Baseline survey	1. Baseline survey on rice grain preferences of farmers, millers and consumers 2. Baseline survey on rice-based products of manufacturers and consumers
	Tertiary	Product formulation	1. Product profiling of quality rice grain 2. Rice-based nutrient dense products formulation (Value added rice-based products) 3. Multiple rice-based food products for disease management 4. Residual effect of herbicides and pesticides of rice grain and rice-based products 5. Proximate analysis of rice-based products 6. Energy estimation 7. Quality analysis of rice-based food products
		Sensory evaluation	1. Quality rice grain selection 2. Rice-based nutrient dense products formulation (Value added rice-based products)
Dissemination	Tertiary	Training	1. Training for food manufacturer, rice miller and RBO miller
		Demonstration	1. Demonstration in bakery and food industries

Table 7. Timeline for implementing the action plan of rice and rice-based products in three decades from 2021-2030, 2031-2040 and 2041-2050

Research Objects		Period 2021-2030						Period 2031-2040						Period 2041-2050					
		Research & Development Phase				Dissemination		Research & Development Phase				Dissemination		Research & Development Phase				Dissemina tion	
	Germplasm in quantity	Primary	Secondary	Tertiary		Tertiary		Primary	Secondary	Tertiary		Tertiary		Primary	Secondary	Tertiary		Tertiary	
		CH	BS	PF	SE	TR	DS	CH	BS	PF	SE	TR	DS	CH	BS	PF	SE	TR	DS
Rice grain characterization	3500				x	x	x			x	x	x	x			x	x	x	x
RBO production	100			x	x	x	x			x		x	x			x		x	x
Puffed rice Production	100			x		x	x			x		x	x			x		x	x
Pooped rice Production	100			x		x	x			x		x	x			x		x	x
Flattened rice production	100			x		x	x			x		x	x			x		x	x
Rice cake Formulation	100																		
Rice biscuit Formulation	100																		

CH: Characterization, BS: Baseline survey, PF: Product formulation, SE: Sensory evaluation, TR: Training, DS: Demonstration

CONCLUSION

Rice is the most valued cereal crop to combat non-communicable diseases (NCDs) with its versatile nutraceutical properties embedded in it. We predicted per capita rice consumption of 365 g and 363 g (dry wt. basis) in 2030 and 2050, respectively will help to attain the current trends of 59.0% of calorie intake from rice only. We expect to increase rice protein from 7.9% to 9% and 10% through our newly released BRRI HYVs which will enable us to increase 12.22% and 26.58% more protein supplementation from rice only in our food table by 2030 and 2050, respectively. Nutraceutically enriched rice-based food items have the potential to be popular among Bangladeshi people. This will play a vital role to gradually reduce overall rice consumption and preferably help sustain food security in Bangladesh in a way to properly utilizing the rice keeping the required dietary allowance intake. Rice-based energy dense dry bakery products can be utilized in the disaster management programme and school feeding nutritional programme for mitigation of malnutrition. Besides, nutraceutical rice-based food formulation requires a lesser amount of carbohydrate so its glycemic load is usually low and these products will help in non-communicable disease management especially diabetics in Bangladesh.

RECOMMENDATIONS

- Nutraceutical enriched rice should be consumed periodically (thrice a week) or should intake a little portion mixed with white rice daily.
- Over polished (>10%) milled rice should not be eaten to avoid bowel related diseases.
- Gluten-free energy-dense rice biscuit (EDRB) has the potential to be utilized for malnutrition minimization approaches including school feeding nutritional programmes and disaster management programme in Bangladesh.
- Nutraceutical enriched such as antioxidant-enriched, micronutrient enriched, anthocyanin enriched rice varieties can be used for rice-based bakery products with a special interest in combating NCDs disease such as cancer, diabetic, and heart disease for the Bangladeshi population.
- Intergovernmental initiatives between the Ministry of Agriculture and Ministry of Disaster Management and Relief can upscale EDRB biscuits as dry food for emergency relief operation and disaster management.

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AUTHORS' CONTRIBUTION

HBS generated idea; MUS, MARS and MAAM coordinated the research; HBS developed methodology; HBS, MAS and NMFR provided scientific insights; HBS, NMFR and MAAM gathered data, carried out analysis and synthesis. HBS did writings for all versions of the manuscript; MUS, MARS, SMHAR and MSK performed critical review and editing; All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

A version of the paper was published in a book 'Doubling Rice Productivity in Bangladesh' in 2020 by the Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh to commemorate BRRI's 50th anniversary. The Bangladesh Rice Journal has prior knowledge of the book publication and does not see any conflict of interest.

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Soil Health as Influenced by Fertilizer Management in Rice Based Cropping System

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ABSTRACT

Nutrient management influences soil health and crop productivity. Sustained crop production requires specific nutrient management options after a certain period. The objectives of this investigation were to examine the effects of inorganic and organic fertilization on yields and soil carbon budget under rice based cropping patterns in Bangladesh. The research data and information have been generated based on previously published, unpublished sources and own concept. Omission of K or imbalanced K are more influential for reduction in grain yield up to 47% in Boro (dry) season but N was most limiting up to 35% in T. Aman (wet) season. With existing fertilizer rates for growing rice, the balances of N and K are always negative. Balanced chemical fertilizer (NPKSZn) can be an option for improving crop productivity and maintain soil quality. Net ecosystem carbon (C) balances are positive when 3 t ha^{-1} cow dung (CD), 2 t ha^{-1} poultry manure (PM) and 2 t ha^{-1} vermicompost (VC) are used in combination with chemical fertilizers. Soil amendments with organic nutrient sources (rice straw, CD, PM, VC, legume crops) and rice based cropping patterns such as T. Aman-Mustard-Boro, Boro-Fallow-Fallow, Jute-T. Aman-Fallow, Wheat-Mungbean-T. Aman, Grass pea- T. Aus-T. Aman and Potato-Boro-T. Aman can be beneficial in improving soil C budget, soil nutrient ratio, total crop production and maintenance of environmental health that will meet SDGs goal.

Key words: Nutrient omissions, yield reduction, cropping pattern, organic nutrient sources, rice.

INTRODUCTION

The average yield of rice has been stagnant and remained lower than the production potential, which might be due to the imbalanced use of fertilizers. Excessive or inappropriate use of chemical, among others, fertilizers is a major cause of nutrient imbalance in soil. Continuous rice culture using sole chemical fertilizer reduces soil quality, carbon sequestration and rice productivity (Haque *et al*., 2019a, c). In such situations, chemical and organic nutrient sources and agronomic management system could be important management options to improve rice productivity and soil quality (Timsina, 2006 and Sihi *et al*., 2017). Huge amounts of chemical fertilizers are generally used by the farmers in Bangladesh, although not in balanced proportion (Biswas *et al*., 2008). The continuous chemical and imbalanced fertilization are considered to be the main issue of rice productivity decline in Bangladesh (Saleque *et al*., 2004). Rice productivity trends were declining in many long-term fertilization experiments under double rice cultures and also in non-rice based double or triple cropping systems (Haque *et al*., 2019a, 2015b and Yadvinder *et al*., 2005). Rice-Fallow-Rice is the most dominant cropping pattern in Bangladesh covering about 27% of the cropland (Nasim *et al*., 2017). The reduction in grain yields was mostly related to a gradual decline in soil nutrients status, soil organic carbon (SOC) content, poor agronomic management practices adopted by the farmers, pest and disease infestation, and changes in the biochemical and physical properties of soil organic matter (SOM) (Haque *et al*., 2015a and Timsina *et al*., 2018). We hypothesize that fertilizer management with varied nutrient combinations influences soil carbon sequestration and rice productivity.

Agricultural management practices such as use of cover crop biomass, farmyard manure, green manure, poultry litter, mustard oil cake, vermicompost, etc not only supply plant

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nutrients; but also affect SOC contents, aggregate stability, water holding capacity, bulk density and finally grain yields (Haque *et al.*, 2019b). It is necessary to assess rice productivity and soil health to sustain rice production as well as soil fertility and to formulate an effective adaptation strategy to minimize yield reduction (Kabir *et al.*, 2020). Food security analysis is important for highly populated and limited cropland areas like Bangladesh that face natural hazards every year. The outputs from such analysis can be utilized by the policy planners to prioritize research and/or to emphasize intensive production in favourable regions. Previous studies mention that only chemical fertilizer application showed negative net carbon balance during rice cultivation (Sihi *et al.*, 2017 and Haque *et al.*, 2019b). Therefore, the objectives of this investigation were to find out the suitable nutrient management options for sustained crop production and net ecosystem carbon budget and development and mapping the action plan for three decades on reducing yield loss from the fertilizer management in rice soil of Bangladesh.

MATERIALS AND METHODS

Experimental design and fertilization

The experiment was initiated on a permanent layout at the BRRI farm, Gazipur, Bangladesh in 1985. Twelve treatments in randomized complete block design (RCB design) with four replications were imposed (Haque *et al.*, 2019a). However, we have considered only NPKSZn, PKSZn (-N), NKSZn (-P), NPSZn (-K), NPKZn (-S), NPKS (-Zn) and control treatments for our analyses and interpretations of findings. Since organic amendments (Cow dung, poultry manure and vermicompost) were used from 2009 to 2019, we have taken those treatments for comparison of rice yield performances with chemical fertilizers. In Boro (dry) season, NPKSZn @ 120-25-35-20-5 kg ha^{-1} was used but in wet season (rainfed wet season) it was 100-25-35-20-5 kg ha^{-1} during 1985-2008. After 2008, NPKSZn was used @ 138-10-80-5-5 kg ha^{-1} and 100-10-80-5-5 kg ha^{-1}, for Boro and T. Aman seasons, respectively based on the soil test. In 2009-2010 dry season, organic materials were used with +PK, +SZn, +KSZn, +PSZn and +PKSZn treatments. Nitrogen as urea, P as triple super phosphate, K as muriate of potash, S as gypsum and Zn as zinc chloride were used as inorganic nutrient sources. Organic nutrient sources used for selected treatments were vermicompost (VC, 2 t ha^{-1}), cow dung (CD, 3 t ha^{-1}), poultry manure (PM, 2 t ha^{-1}) in +PSZn, +KSZn, and +PKSZn treatments. Only N @ 138 kg ha^{-1} was applied as top dress in organic nutrient added plots. Table 1 shows nutrient composition of organic materials.

During 1985-2008, BR3 and BR11 were used as indicator rice varieties in Boro and T. Aman seasons, respectively. From 2009 onward BRRI dhan29 and BRRI dhan49 were used in Boro and T. Aman seasons, respectively. Rice was transplanted in the first week of January and harvested in May for Boro season and T. Aman rice was transplanted in the first week of August and harvested in the third week of November. Two to three rice seedlings (45–50-day-old in dry season and 25–35-day-old in wet season) were transplanted at 20-x 20-cm spacing.

Table 1. Nutrient compositions of cow dung, poultry manure and vermicompost.

Organic material	% N	% P	% K	% S	% Zn
Cow dung	0.51	0.15	0.50	0.00	0.00
Poultry manure	1.90	0.56	0.75	1.10	0.02
Vermicompost	2.00	0.52	0.42	0.30	0.03

Urea N was applied in three equal splits at final land preparation, active tillering stage, and 5-7 days before panicle initiation (PI) stage equally for both seasons. Rest of the fertilizers were applied at final land preparation. The crop was harvested at maturity and grain yield was recorded at 14% moisture content and straw yield as oven dry basis.

Carbon balance

Soil organic carbon (SOC) stock was determined as follows: SOC stock = SOC*soil depth*bulk density ....(i)

Action plan development

Consultant opinion has been used for making the action plan for better fertilizer management and rice yield production during 2021-2050.

RESULTS AND DISCUSSIONS

Changes in rice productivity and nutrient balance

Inorganic chemical fertilizer treatment (NPKSZn) produced significantly ($P<0.05$) higher mean grain yield than omissions of selected nutrients in both T. Aman and Boro seasons (Table 2).

Omission of sulfur (S) in both seasons had positive response for higher grain yields including Zn in only dry season. There was around 26% yield advantage in Boro season compared to T. Aman season, but no significant straw yield differences between the seasons for the same treatment. Grain yield reductions because of N, P and K were more prominent in Boro season than in T. Aman season (Fig. 1). In general, grain yield reductions in Boro season varied from 25-45%, 2-40%, and 2-47% for N, P and K, respectively might be because of the climate effect. Similarly, in T. Aman season, yield reductions were 5-35%, 2-15%, and 3-22% for N, P and K omissions, respectively. Nitrogen and K balance were negative in both the seasons but P balance was positive except for P omission and control treatments (Figs. 2 and 3).

Inorganic and organic nutrient sources on yield

Continuous application of different C sources increased grain yield than complete chemical fertilization during 2010-2019. In conventional complete chemical fertilization, grain yields were in static position; but grain yield increasing trends were higher with organic nutrient sources (Fig. 4).

Table 2. Grain and straw yields of rice as influenced by fertilizer management under a Rice-Fallow-Rice cropping system for 35 years in BRRI, Gazipur.

Treatment	T. Aman season		Boro season	
	Mean yield (t ha^{-1})			
	Grain	Straw	Grain	Straw
NPKSZn	4.28a	5.25a	5.35a	5.40a
PKSZn (-N)	3.56c	4.38b	3.26c	3.35c
NKSZn (-P)	3.93b	4.87a	3.95b	4.54b
NPSZn (-K)	3.56c	4.79a	3.92b	4.47b
NPKZn (-S)	3.86b	5.24a	5.22a	5.16a
NPKS (-Zn)	4.24a	5.11a	5.22a	5.23a
Control	3.05d	3.60c	2.34d	2.65d

Note: Means within each row followed by same letter do not differ significantly at $P<0.05$ level using Tukey's HSD test.
Source: Haque *et al.*, 2019a; BRRI Annual Research Review, 2019

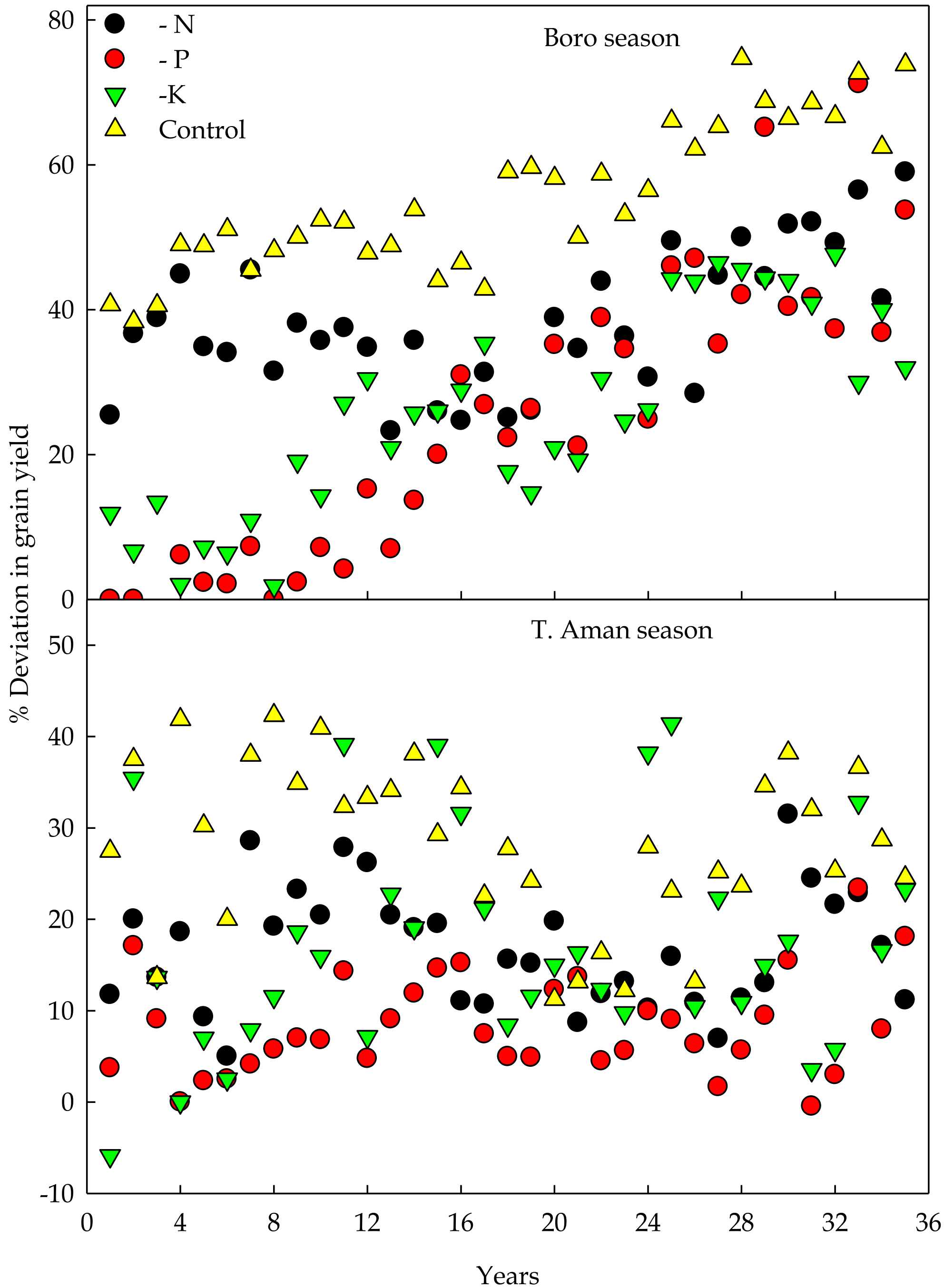

Fig. 1. Percentage changes in grain yields because of omissions of N, P, K compared to NPKSZn fertilization during 1985-2019, BRRI, Gazipur, Bangladesh (Haque *et al.*, 2019a; BRRI Annual Research Review, 2019).

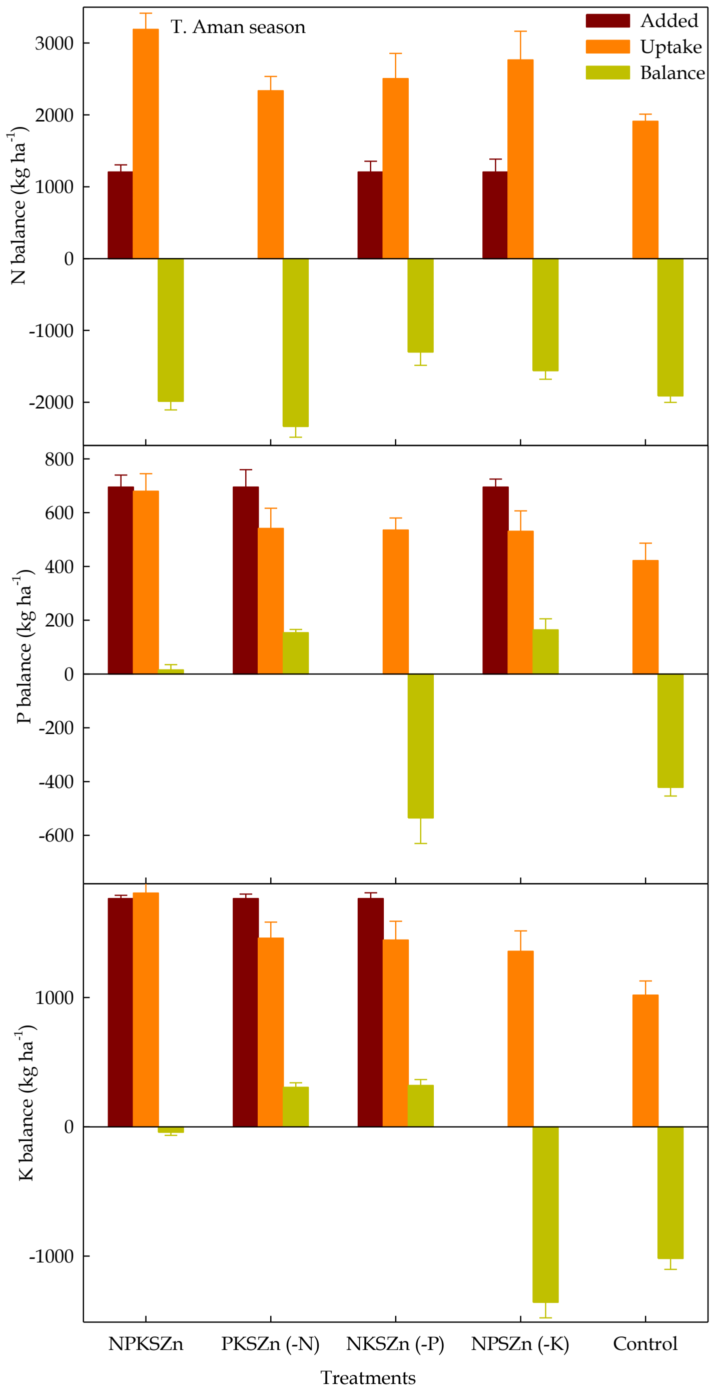

Fig. 2. Changes in mean N, P and K nutrient balances after 35 years of fertilization under Rice-Fallow-Rice cropping system in wet season. [Bars indicate mean value ± standard error (n=3). (Haque *et al.*, 2019a; BRRI Annual Research Review, 2019)].

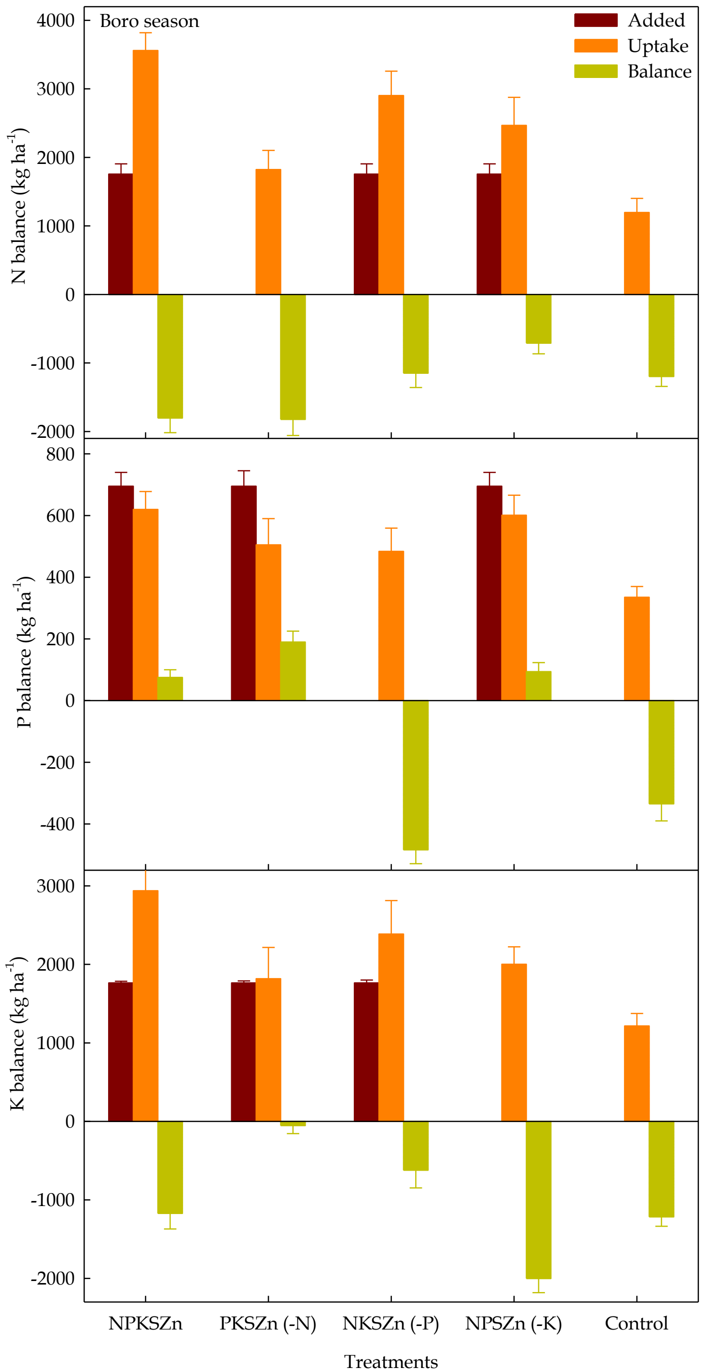

Fig. 3. Changes in mean N, P and K nutrient balances after 35 years of fertilization under Rice-Fallow-Rice cropping system in Boro season. [Bars indicate mean value ± standard error (n=3). (Haque *et al*., 2019a; BRRI Annual Research Review, 2019)]

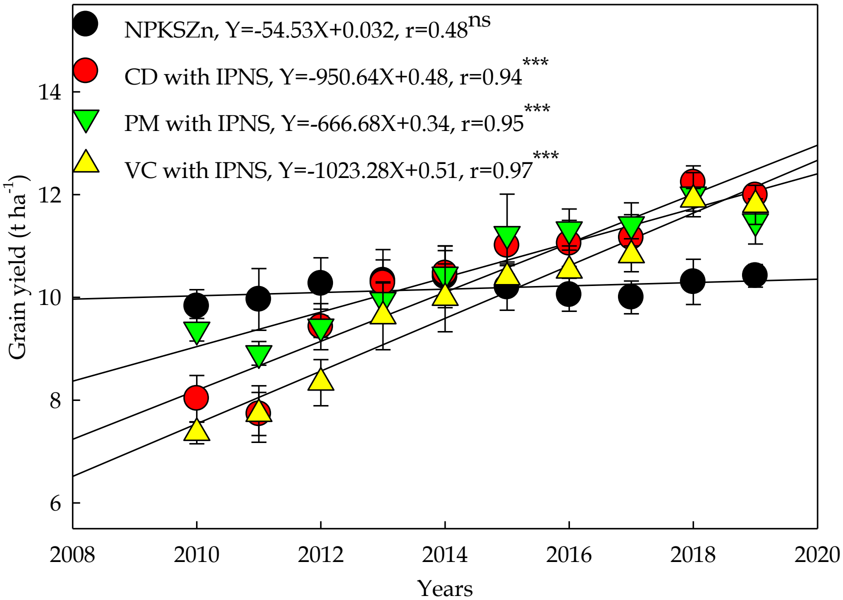

Fig. 4. Changes in annual rice yield under inorganic and organic amendments for 10 years. [Bars indicate mean value ± standard error (n=3); ns and *** mean non-significant and significant at P≤0.001, respectively]. [Note: CD with IPNS = Cowdung with integrated plant nutrient system, Poultry manure (PM), vermicompost (VC) (Haque *et al.*, 2019a; BRRI Annual Research Review, 2019)].

Rice productivity and nutrient use-efficiency varied significantly (P<0.05) under inorganic fertilization over the seasons for 35 years in Rice-Fallow-Rice cropping pattern because of varietal differences and weather variations. Average rice productivity with NPKSZn treatment was about 5.35 and 4.28 t ha^{-1} in Boro and T. Aman seasons, respectively. It would be necessary to increase such yield levels to 8.0 t ha^{-1} by 2030 to meet the rice demand in Bangladesh. To do so, we have to cultivate nutrient use-efficient varieties along with the adoption of proper nutrient management systems. Although N is the most limiting nutrient to improve rice grain yield in Bangladesh including other Asian countries, P and K deficiencies also play antagonistically against higher yields. There is widespread mining of K in Bangladesh along with emerging new nutrient deficiencies (Biswas *et al*., 2017) that should be addressed for sustained rice production in Bangladesh. We have also found negative contributions of N, P and K if not used rationally (Fig. 1). However, global concerns are about the over use of inorganic fertilizers that impair environments (Laegreid *et al*., 1999) and contribute to soil acidity and contaminates the ground water resources (Bijai *et al*., 2008). In solving such a dilemma, the use of indigenous nutrients and added ones should be tuned up depending on crop requirements. As rice productivity was declining under fixed fertilizer management in a Rice-Fallow-Rice system, new avenues of nutrient management options were investigated to improve rice productivity. After 35 years, K balance was -1350 to 320 kg ha^{-1} in wet season and -60 to -2000 kg ha^{-1} for dry season.

Organic matter and different nutrient deficiency status

About 35-79% of areas are deficit based on major nutrient elements and organic matter in different regions of Bangladesh (SRDI, 2020). Therefore, many management practices are needed to recover the nutrient status as well as increased yield productivity in Bangladesh (Table 3).

Soil properties and net carbon budget

Continuous rice cultivation without fertilization for 35 years significantly ($P<0.05$) deteriorated studied soil chemical properties except for P status (Table 4). Continuous P applications significantly ($P<0.05$) increased total and available soil P contents. In the control treatment, C balance was significantly negative (-101 kg C ha^{-1}, $p<0.05$) compared to the other treatments after 35 years in Rice-Fallow-Rice systems; but the magnitude of such negative balance was almost half (-60 kg C ha^{-1}) when NPKSZn fertilizers were added (Fig. 5). Among the organic nutrient sources, C balance did not vary significantly through C sequestration which was about 94–95 kg C ha^{-1}.

The negative C balance can be improved through the adoption of different cropping patterns. For example, C balance was positive with T. Aman-Mustard-Boro and Jute-T. Aman-Fallow patterns (Fig. 6). The SOC is generally low in soils of Bangladesh. So, the continuous addition of CD and PM with IPNS fertilization for nine years increased SOC balance (Fig. 5). Addition of organic C alleviated soil health and thus there was higher C sequestration because most of the C added from organic sources were in recalcitrant forms. The addition of organic nutrient sources can also help in reducing the amounts of inorganic fertilizers for rice production. Moreover, choice of suitable cropping pattern(s) would be necessary not only to diversify crop production but also to improve C sequestration. Besides, greenhouse gas emissions in relation to inorganic fertilizer production can be reduced through the use of organic nutrient sources and based on patterns and varieties. So, policy intervention and improved dissemination techniques for the application of organic nutrient sources should be strengthened not only for increased rice production but also to maintain soil fertility.

Table 3. Deficit soil nutrient status of Bangladesh.

Nutrient status	Area (lac ha)	Percentage (%)	Optimum value
Phosphorus	66.0	44.7	8 ppm
Potassium	52.7	35.7	0.12 meq^{-1} 100 g soil
Sulfur	65.3	44.2	10 ppm
Zinc	55.5	37.6	0.6 ppm
Boron	51.5	34.6	0.2 ppm
Organic matter	116.4	78.9	Up to 5%

Source: SRDI, 2020

Table 4. Soil properties as influenced by fertilizer management after harvesting of 35 years of nutrient amendment, Bangladesh Rice Research Institute, Gazipur, Bangladesh.

Parameter	Initial	Treatment			
		NPKSZn	PKSZn	NKSZn	NPSZn
pH (1:5 with H_2O)	6.78	6.96a	6.67b	6.71b	6.76b
Organic carbon (g kg^{-1})	12.2	11.8a	11.9a	11.8a	11.9a
Total N (g kg^{-1})	0.08	0.12a	0.10a	0.11a	0.11a
Total P (mg kg^{-1})	-	346c	449a	137d	420b
Olsen P (mg kg^{-1})	9.8	22b	30a	3c	22b
Total K (g kg^{-1})	-	4.25a	3.81b	4.17a	3.67c
Exchangeable K (mg kg^{-1})	70	54a	54a	50b	38c

Note: Means within each row followed by same letter do not differ significantly at $P<0.05$ level using Tukey's HSD test.
Source: Haque *et al.*, 2019a

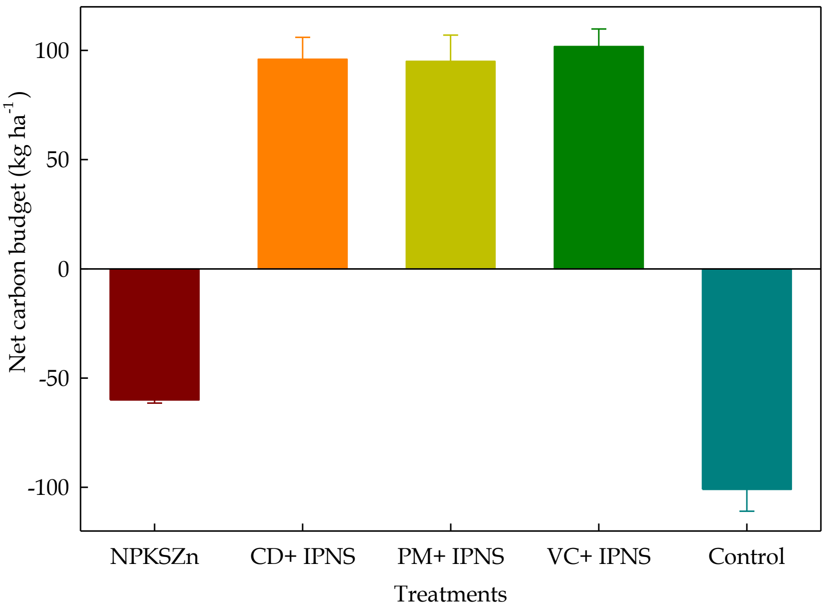

Fig. 5. Soil organic carbon stock and its budget as influenced by organic and inorganic amendments, BRRI, Gazipur, Bangladesh. Note: CD+IPNS = Cowdung with integrated plant nutrient system, Poultry manure (PM), vermicompost (VC) (Haque *et al.*, 2019a). Net carbon budget = Total input carbon-Total output carbon.

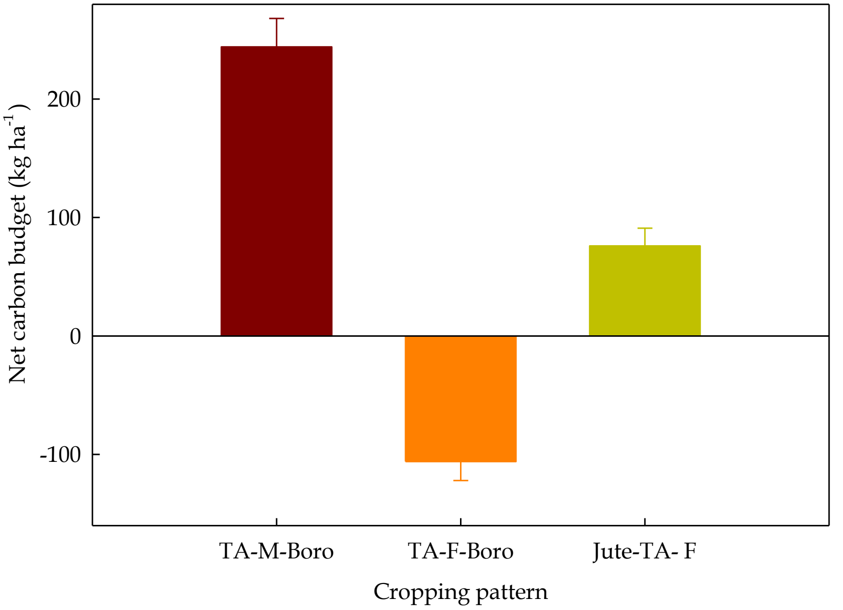

Fig. 6. Net carbon balance as influenced by cropping patterns at farmer's field, Kishoreganj, Bangladesh. [Note: TA-M-Boro=T. Aman-Mustard-Boro, TA-F-Boro= T. Aman-Fallow-Boro, Jute-TA-F= Jute-T. Aman-Fallow (Haque *et al.*, 2020)].

Action plan

Management strategies will be helpful for maintaining soil carbon balance as well as crop productivity at the farmer's level. The yield target will depend on different fertilizer management practices in different regions of Bangladesh (Fig. 7).

The nutrient composition will be determined based on selection of nutrient composition (Table 5) during the study period. Action plan activities will be undertaken for conscious build up with balanced chemical fertilizer application, ensuring any kinds of organic fertilizer sources, retaining crop residue (such as rice straw up to 25-30 cm incorporated into rice soil), nano chemical fertilizer application, slow-release fertilizer application (Nymph coated, sulfur coated, etc.), leguminous crops incorporation, training arrangd for the amenities of organic and inorganic fertilizer uses to the farmers and extensions personal for awareness of soil carbon balance and increased crop production (Table 6).

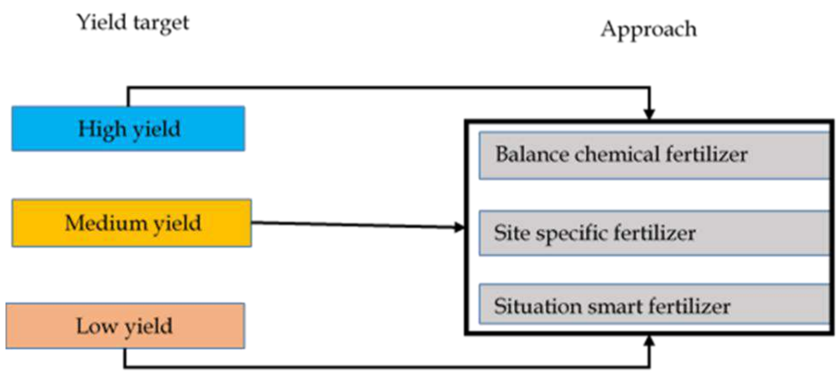

Fig. 7. Yield target based different fertilizer management.

Table 5. Selection of nutrient composition will be influenced under inorganic and organic fertilizer management.

Theme	Activity	
Nutrient composition	Inorganic	Organic
	• Ackage mix fertilizer • Nutrient composition • Nano chemical fertilizer • Slow-release chemical fertilizer	• Retain crop residue (such as rice straw up to 25-30 cm incorporated into rice soil) • Ensure any kinds of organic fertilizer requirement • Leguminous crops incorporation

Table 6. Action plan strategies will be helpful for maintaining soil carbon balance and crop productivity.

Theme	Programme	2021-2030	2031-2040		2041-2050
Research and development	Yield target-based fertilizer management	Continue improving	Follow up	Continue improving	Follow up
	Nutrient composition	Continue improving	Follow up	Continue improving	Follow up
	Net carbon balance	Continue improving			
	Reduce atmosphere CO_2	Continue improving			
Extension	Training for farmers and extension personal	Continue			
	Field demonstration	Continue			
	Promotional activities	Continue			

System recommendation

The action plan will be implemented through the system recommendation process. System recommendation is one of the important techniques for increasing yield productivity as well as maintaining good soil health (Fig. 8). The major steps for mapping and understanding the system recommendation are (i) system identification based on cropping pattern, soil and land typology, and agro-ecosystem; (ii) technology innovation, testing, and calibration; and (iii) validation. The whole process will be evaluated and executed through field survey, field experience, research and development on cropping pattern, land typology and ecosystem, field trial and feedback. Therefore, systematic implementation of the system recommendation will help for reducing production costs and increased economic benefit to the farmers under different agro-ecological zones of Bangladesh.

CONCLUSION

Different types of organic fertilizer sources can be considered as one of the best management options for increasing rice productivity and soil carbon balance. Continuous omissions of N, P, K, S, and Zn reduced grain yields compared to NPKSZn fertilization with variable ranges depending on the growing season. The influence of N, P, K, S and Zn omissions on grain yield was in the order of N>K>P>S>Zn in Aman season and that of K>N>P>S>Zn in Boro season indicating that season specific nutrient rate adjustment, balanced chemical fertilizer, and organic fertilizers would be required for sustained rice production and soil health in Bangladesh. Action plan will be helpful for

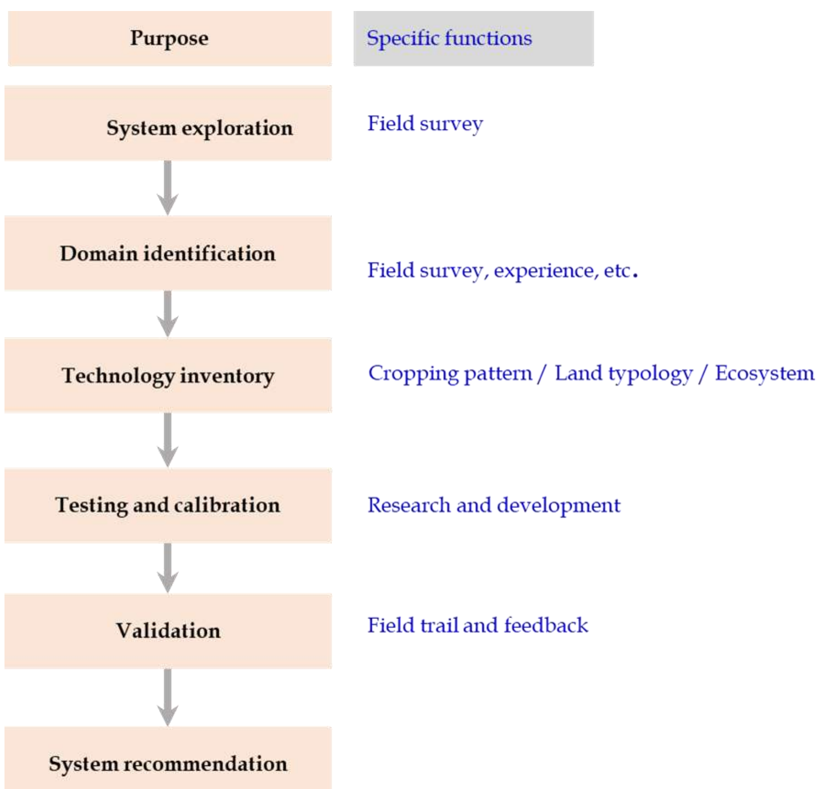

Fig. 8. Some activities will be helpful for making system recommendation.

enhancing productivity and minimizing production costs. Balanced chemical fertilizer, organic amendments, and adoption of rice-based cropping patterns can be beneficial in maintaining soil carbon balance and total crop production along with maintenance of environmental health that will meet SDG's target.

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AUTHORS' CONTRIBUTION

MMH, MUS, and MSK generated idea; MARS and MAAM coordinated the research; MMH developed methodology; MMH, MRI, MSR, MARS, MUS and MSK provided scientific insights; MMH gathered data, carried out analysis and synthesis; MMH did the writings for all versions of the manuscript; MSK, MUS, MSR, MARS and MAAM performed critical review and editing. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

A version of the paper was published in a book 'Doubling Rice Productivity in Bangladesh' in 2020 by the Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh to commemorate BRRI's 50th anniversary. The Bangladesh Rice Journal has prior knowledge of the book publication and does not see any conflict of interest.

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Integrated Weed Management Strategies for Sustainable Rice Production in Bangladesh

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ABSTRACT

Weed causes huge reduction in crops yield, increases cost of cultivation, reduces input efficiency, interferes with agricultural operations, impairs quality, act as alternate hosts for several insect and diseases .Yield loss due to improper weeding at farmer's field ranged from 4 to 22% depending on different rice ecosystem in Bangladesh. But at present considering all the cultivable land across the country and other issues; yield loss due to weeds considered about 2% in a consultation meeting.The present weed control practices in Bangladesh are characterized by intensive use of manual labour, use of herbicide and certain mechanical weeding. Manual weeding, besides laborious is inefficient as it is not done in time in most of the cases and always not practical because of various adverse conditions. Cost effective and integrated weed management system should be adopted to increase economic gain and sustainable rice production. Adopting timely and effectively appropriate weed management techniques we can reduce a significant amount of yield loss and about 0.43 million ton (MT) additional yield could be increased by 2030. To achieve the target weed management should be done from the very beginning of rice production and up to 30-35 DAP (days after planting) for Aus season, 35-40 DAT (days after transplanting) for T. Aman season and 40-45 DAT for Boro season which indicates critical period of weed infestation in Aus, T. Aman and Boro season. The main approach is that rice field have to keep free from weed up to that days by 2/3 hand weeding (HW) or application of herbicide fb (Followed by) 1HW or applying weeder fb 1HW which is called integrated weed management. Herbicide should be applied at proper time and dose which reduce 61% weeding cost. Mechanical weeding (MW) reduces 50% weeding cost that keeps environment friendly. Future weed science research specially herbicide efficacy with correct time and dose, new molecule herbicide with low environmental effect, herbicide residues in soil plant system, bioherbicide, allelopathic variety, weed competetive variety, mechanical weeder with related technological developments need a multidimensional approach for ecologically sustainable integrated weed management. Such a system will work toward a socially permissible, environmentally sound, economically feasible, productive and sustainable agricultural system.

Key words: Rice weed, Eco- friendly weed management , herbicide

INTRODUCTION

Weeds reduce rice yield by competing for space, nutrients, light, and water, and by serving as hosts for pests and diseases. Under farmers' conditions, sometimes weed control is not generally done properly or timely, resulting in severe yield reduction. Weeds are recognized as major biological constraints that hinder the attainment of optimal rice productivity in Bangladesh.During peak periods of labour demand, weeding often is done late, causing drastic losses yield in rice. Farm families typically are unable to do all their own weeding and need to hire labor. Two to three HW or MW by BRRI weeder including HW in the plant to plant gap or herbicide application followed by a HW (if needed) are easier, cost-effective and the latest weed management options in rice cultivation in Bangladesh (Bhuiyan *et al.*, 2011; BRRI, 2014). The yield gap was as high as 1 t ha^{-1} with 30% of farmers losing in excess of 500 kg ha^{-1} (Ahmed *et al.*, 2001) for improper weeding. In direct wet seeded rice about 82% yield loss occurs if not weeded (Bhuiyan, 2016). Table 1 presents yield loss percentage due to improper weeding in the farmer's field in Bangladesh which is reportedly 4.25 to 20% depending on different rice cultures (BRRI, 2006, Bhuiyan *et al.*, 2018). Weeds were reported to cause yield loss of 5% in commercial agriculture, 10% in semi-commercial agriculture, 20% in subsistence

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agriculture in India (Choudhury and Singh, 2015). The contribution of production factors to rice grain yield depends on seasons and ecosystems. Fertilizer largely contributes to rice yield in all the ecosystems followed by weed control. Each rice ecosystem has a critical period of weed infestation. After that grain yield reduces drastically for each day crop weed competition. Weed management strategies diverted from non-chemical weed management to the use of herbicide options for not only increasing its availability and selective effectiveness but also become popular due to shortage of labour and cost-effectiveness. Hence, there is a great need to popularize cost-effective weed management technologies. Though the increased number of herbicides introduced into the market is a reflection of the popularity of the herbicides as a tool for weed management. Systematic studies to assess the impact of improved weed management technologies are required in Bangladesh. Effective weed control requires knowledge of the names, distribution, ecology, and biology of weeds in the rice-growing regions. No single weed-control measure gives continuous and best weed control in all situations. Various weed control methods including complementary practices, hand weeding, mechanical weeding, chemical weeding, biological control, and integrated approaches are available (De Datta, 1981). These methods need to be fine-tuned for specific regions, ecosystems, cropping systems, and economic groups.

Consequently, there is a great need for a new weed management paradigm in modern agriculture (Bajwa, 2014) based on ecological principles and non conventional weed management approaches. These approaches may offer more durable weed management solutions to lessen problems of herbicide resistance, environmental pollution, weed diversification, weed invasion, and yield losses (Chauhan, 2013; Singh, 2007; Travlos, 2013). Even more, these approaches will facilitate the development of integrated weed management (IWM) strategies which could spearhead the strengthening and broadening of the eco-physiological and evolutionary basis of weed science. The "many little hammers" concept (Liebman and Gallandt, 1997) and the "use of technological advancement" (Young *et al*., 2017) are two major IWM components that are gaining momentum (Menalled, 2018). As the number of herbicide-resistant weed ecotypes increases and the discovery of new herbicide modes of action (MOAs) declines (Strek, 2014), the need to utilize all available weed management options is crucial.

This study presents a review of modern technologies and approaches and new uses of old technologies and tools suitable for IWM. Following three opinions to be considered for sustainable rice yield; (i) Minimizing rice yield loss by appropriate weeding; (ii) Productivity could be increased by safe use of herbicide; and, (iii) Environmentally and sustainable integrated weed management practices. With the above background, this paper undertook four specific objectives in relation to rice weed management in Bangladesh: (i) Presentation of the changing status of weed management options (ii) Management status of major weeds in rice ecosystem and their dominance ranking (iii) Highlighting the scenarios of yield loss associated with improper weeding; and, (iv) Development and mapping the action plan for three decades on reducing yield loss from the weeds.

MATERIALS AND METHODS

Yield loss from improper weeding in the farmers' field was determined by performing a group discussion of agronomists, statisticians, and other scientific personnel with the current secondary and reviewed data. It was assumed realistic yield loss from improper weeding in different rice cultures in different agronomic management was about 1.9% (Kabir *et al.,* 2020). It has been reviewed from different experimental data that different weed management practices like hand weeding in improper time, selection of wrong herbicide, herbicide applied in inappropriate time, lacking knowledge of crop weed competition may reduce a certain level of yield. Table 2 presents the baseline yield loss data from different agronomic management (including yield loss from weeds). Action plans for 2021-2030, 2031-2040, and 2041-2050 for minimizing yield loss due to weeds were developed considering available weed management options. New options like bioherbicide and development of allelopathic variety were also considered. Moreover, the residual effect of herbicide in grain and straw and soil microorganism studies was also taken into consideration.

RESULTS AND DISCUSSION

Minimizing yield loss by appropriate weeding

Assessment of crop yield and economic losses due to weeds in rice is an important aspect of this study which helps in formulating appropriate management strategies against weeds. In general, the yield loss due to weeds is almost always caused by a group of different weed species, and these weeds may have substantively different competitive ability (Weaver and Ivany, 1998; Milberg and Hallgren, 2004). Practically, it is very difficult to estimate the yield loss due to single weed species, and therefore, it is estimated as the collective efforts by all the weeds. Most of the studies conducted in the past are more or less based on the experimental data which may not be always representative for field situation. Although estimation of yield losses from the experimental situation is subjected to local effects and sometimes it is valid only for some cropping situation, it may be difficult to extrapolate the results for farmers' yield losses (Milberg and Hallgren, 2004). Further, it is more realistic to establish results from field trials comparing the different treatments in the farmers' field (Walker, 1983; Zanin *et al*., 1992; Oerke and Dehne, 1997; Tamado *et al*., 2002). Yield data of farmers’ practice are used to estimate actual yield losses in different crops whereas; yield data of weedy check plot are used to estimate the potential yield loss in relation to weed-free situation. Actual and potential yield losses usually calculate using following formulas as given in Milberg and Hallgren (2004); Galon and Agostinetto (2009); Soltani *et al*. (2016):

Actual yield loss due to weeds

$$= \left(\frac{WFy - FPy}{WFy}\right) \times 100 \ldots \ldots \ldots \ldots \text{(i)}$$

Potential yield loss due to weeds

$$= \left(\frac{WFy - WCy}{WFy}\right) \times 100 \ldots \ldots \ldots . (ii)$$

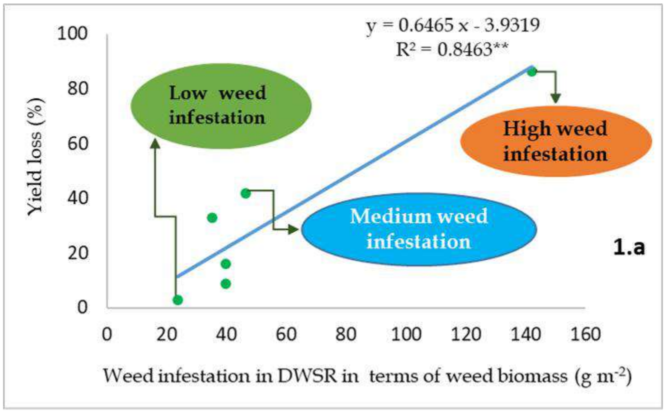
Where, WFy – crop yield in weed-free situation, FPy – crop yield in farmers' practice, and WCy – crop yield in weedy check plot.

Grain yield losses due to weed competition would be less severe under the transplanting method than those under direct-seeding. Globally, rice yield losses due to weeds have been estimated at 10% of total production (Oerke and Dehne, 2004). Table 1 shows yield loss due to improper weeding in different rice cultures in Bangladesh and major rice-growing countries in Asia depending on different rice cultures. Rice yield losses (%) due to uncontrolled weed growth, improper weeding and weed competition were least (4.25%) in transplanted rice (Bhuiyan *et al*., 2018), although it varies from 40-100% in direct-seeded rice in Bangladesh. In India, it varies 12-69% in transplanted rice and 17-98% in direct-seeded rice. In different countries yield loss (%) varies depending on different rice cultures and weed management issues. In India, the study revealed that potential yield losses were high in case of direct-seeded rice (15–66%) and transplanted rice was 13.8% (Gharde *et.al*., 2018). It has been estimated that rice yield decreases by 0.75 kg for every 1 kg of weed biomass produced (IRRI, 2003).

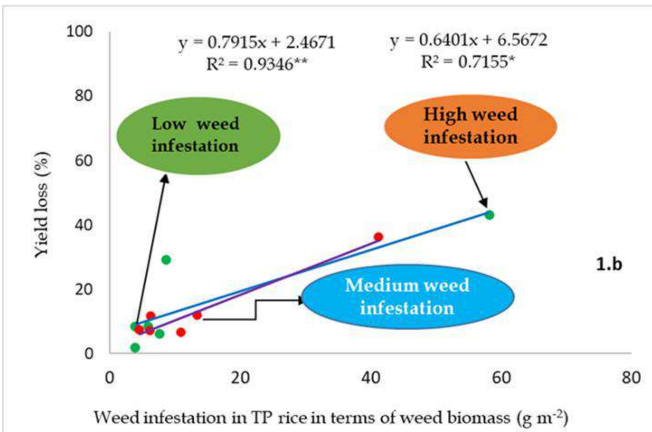
Yield loss due to weeds is dependent mainly on the growth of weed biomass. There is a linear relationship between yield loss (%) and weed infestation. Figure 1 indicates that higher the weed infestation in terms of weed biomass higher the yield loss. It varies from 2-82% depending on weed control measures in transplanted and direct-seeded rice. Weed biomass (Fig. 1a) was calculated from the model, y= 0.6464x-3.9319, $R^2 = 0.8463^{**}$ where Y = % yield loss, x = weed biomass. The equation showed that the coefficient of weed biomass (g m^{-2}) is 0.6465, indicated that increase in every additional biomass we expect a certain % of yield loss of rice. From the equation estimated weed biomass accumulation was 21.54 g m^{-2} considering 10% yield loss in direct-seeded rice. In transplanted rice (Fig. 1b) it is estimated an average of 7.44 g m^{-2} weed biomass if considered 10% yield loss. But we have to reduce yield loss up to a certain level from 2021 to 2030 and beyond gradually. Uncontrolled weed growth occurred the highest weed infestation that caused the highest yield loss. Farmers who control weed but not timely and effectively cause medium weed infestation and yield loss. Where weed infestation is naturally less and weeded timely and accurately poses low weed infestation and minimum yield loss. Need to take necessary measures to reduce weed infestation at a low level by using different weed management tools timely and effectively. In that case, we have to follow integrated weed management options to keep yield loss minimum. In a consultation meeting of BRRI with agronomists, weed scientists and economists considered that national yield loss due to weeds may 1.9% (Kabir *et al*., 2020). We projected yield loss will be decrease @ 10% in each five years with appropriate and proper weeding. Thus yield loss from weeds will be decreased from 1.9% to 1.33% in 2030. As a result yield loss will be minimized and about 0.43 million ton of additional clean rice would be produced.

Table 1. Yield loss due to weeds in rice established by different methods in Bangladesh and major rice-growing Asian countries.

Country	Yield loss (%)		Reference
	Transplanted rice	Direct seeded rice	
Bangladesh	15-40	40-100	Ahmed *et al*., 2005; Mazid *et al*., 2001 (Used different weed control methods)
	22.36 (Modern Boro)	-	Mamun (1990) (Improper weeding)
	8.69 (Boro)	-	IRRI, 2003; BRRI, 2006 (Improper weeding)
	14-48 (T. Aman)	-	Mamun (1990) (Improper weeding)
	-	20.07 (Aus)	IRRI, 2003; BRRI, 2006
	40 - 58.96 (T. Aman)	-	BRRI, 1981 (Two season experiment); Mamun, 1990 (A review article); Sarker 1996 (Field experiment, used different weeding methods)
	12.35 (T. Aus)	-	IRRI, 2003; BRRI, 2006
	4.25 (Boro and Aman)	-	Bhuiyan *et al*., 2018 (Used different weed control methods)
India	12-69	17-98	Kathirvelan and Vaiyapuri 2003; Rammohan *et al*., 1999; Singh *et al*., 2011
Pakistan	24-56	80	Hussain *et al*., 2008; Khaliq *et al*., 2011
Nepal	7-70	14-93	Pandey, 2009; Ranjit *et al*., 1989
Srilanka	20-40	20-40 or higher (WSR)	Chauhan *et al*., 2013; Marambe 2009; Marambe *et al*., 2015
Philippines	-	11-63	Rao and Moody, 1994; Zhao, 2006
South Korea	-	40-100	Kim and Ha, 2005
Malaysia	-	10-35	Karim *et al*., 2004



Source: Bhuiyan (2016)



Source: Ahmed *et al.* (2005)

Fig. 1a-1b. Yield loss due to weed infestation in transplanted and direct-seeded condition.

Table 2. Yield loss (%) due to different agronomic factors.

Agronomic factor	Yield loss (%)
Time of sowing/transplanting	4.75
Seedling age	2.50
Spacing	1.20
Weeds	**1.90**
Fertilizer (dose and timing)	4.00
Other agronomy management (seed quality, tillage etc)	1.00
Total	15.35

Source: Adopted from Kabir *et al.*, 2020

When to weeding to overcome yield loss?

The climate of Bangladesh is hot and humid which favours weeds to germinate vigoursely. Weeds commonly found in Bangladesh about 350 species are recorded in Asian countries, these weeds cause roughly 33% of total crop loss in different crops (CIMMYT, 2011). The number of species and density of weed in an area depends on the land use pattern, associated crops, and its ecological conditions. Among the weed species commonly found, about one-third of plants are monocotyledonous and the remaining plants are dicotyledonous. There are many weed grows in the rice field of Bangladesh. From which Tables 3 and 4 list nine harmful[1] weeds in lowland rice and ten harmful weeds in upland rice (BRRI, 2006).

Table 3. List of nine major harmful weeds of lowland in Bangladesh.

Common name	Scientific name	Group
Shama	*Echinochloa crus-galli*	Grass
Gaicha	*Paspalum disticum*	Grass
Halde mutha	*Cyperus difformis*	Sedge
Bara chucha	*Cyperus iria*	Sedge
Bara javani	*Fimbristylis miliacea*	Sedge
Chechra	*Scripus maritimus*	Sedge
Pani kachu	*Monochoria vaginalis*	Broad leaf
Jhil marich	*Sphenochlea zeylanica*	Broad leaf
Pani long	*Ludwigia octovalvis*	Broad leaf

*Photograph of weeds have been listed in appendix 1a

Table 4. List of ten major harmful upland weeds in rice field.

Common name	Scientific name	Group
Khudey shama	*Echinochloa colona*	Grass
Durba	*Cynodon dactylon*	Grass
Ulu	*Imperata cylindrica*	Grass
Chapra	*Elusine indica*	Grass
Kakpaya grass	*Dactyloctenium aegyptium*	Grass
Anguli grass	*Digitaria sanguinalis*	Grass
Mutha	*Cyperus rotundus*	Sedge
Kesuti	*Eclipta allba*	Broad leaf
Kata notey	*Amaranthus spinosus*	Broad leaf
Kanainala	*Commelina diffusa*	Broad leaf

*Photograph of weeds have been listed in appendix 1b

The summed dominance ratio (SDR) is more informative than any single measure in reflecting the contribution of a species in the community. It indicates the most harmful and dominating weed species grown in a crop field. Table 3 and 4 indicate topmost harmful weeds in lowland and upland conditions found in Bangladesh. Based on harmful effect, dominance, and aggressivity. Some dominating weeds were identified in transplanting and direct seed rice in Table 5. The most dominant weed species were arranged in the order of *Echinochloa crus-galli* > *Scirpus juncoides* > *Cynodon dactylon* > *Monochoria vaginalis*> *Cyperus iria*> *Cyperus difformis*> *Sphenoclea zeylanica* >*Fimbristylis miliacea.* In different agricultural regions, it almost originates similar with little variations on different ecosystems.

Table 6 shows a critical period of weed infestation in Aus, Aman, and Boro seasons. The main principle is that we have to keep rice weed-free up to that time by 2/3 HW (hand weeding) or application of herbicide fb (Followed by) 1HW or applying weeder fb 1HW. We have to prevent competition of weed and rice. These techniques involved integrated weed management. Not a single method is enough to control weeds in time properly. Integrated weed management could be followed for minimizing yield loss due to improper weeding (Table 7). Farmers can follow hand weeding, weeder, or herbicide whatever they choose. However, weed management should be done from the very beginning of rice production and specific stage of the rice life cycle.

Different weed management options

During land preparation

- Weed control during land preparation is crucial to reduce the amount of weed pressure in the field.
- Land preparation should start at least 7-10 days before planting. Plowing destroys weeds and remaining stubbles from the previous crop.
- Weeds should be allowed to grow before the next cultivation. In addition, the proper leveling of field helps to retain a constant water level that controls weeds.

Weed control in the nursery

- Land should be prepared two weeks before seeding.
- If there are weed seedlings in the nursery bed, separate them from rice seedlings during pulling and bundling to avoid planting weeds.

[1]A harmful weed is a weed that has been designated by an agricultural or other governing authority as a plant that is injurious to agricultural or horticultural crops, natural habitats or ecosystems, or humans or livestock.

Table 5. Weed dominance ranking (most harmful weeds) in rice cultivation.

Dominance ranking	Weed	Reference
	Transplanted rice	
1	*Echinochloa crus - galli*	
2	*Scirpus juncoides*	
3	*Cynodon dactylon*	Bhuiyan *et el.*, 2017
4	*Cyperus difformis*	
5	*Marsilea minuta*	
6	*Monochoria vaginalis*	
	Transplanted rice	
1	*Cyperus difformis*	
2	*Echinochloa crus - galli*	
3	*Scirpus juncoides*	
4	*Monochoria vaginalis*	Mahbub and Bhuiyan, 2019
5	*Marsilea minuta*	
6	*Cynodon dactylon*	
7	*Sphenoclea zeylanica*	
8	*Eclipta alba*	
	Direct seeded rice	
1	*Scirpus juncoides*	
2	*Echinochloa crus - galli*	
3	*Cynodon dactylon*	
4	*Cyperus iria*	
5	*Cyperus difformis*	
6	*Sphenoclea zeylanica*	Bhuiyan, 2016
7	*Monochoria vaginalis*	
8	*Marsilea minuta*	
9	*Lindernia floribanda*	
10	*Leptochloa chinensis*	
11	*Ludwigia octovalvis*	
12	*Fimbristylis miliacea*	
	Transplanted rice	
1	*Echinochloa crus - galli*	
2	*Scirpus juncoides*	
3	*Monochoria vaginalis*	
4	*Cyperus iria*	
5	*Digitaria sanguinalis*	
6	*Leersia hexandra*	Islam *et al*., 2017
7	*Panicum repens*	
8	*Cyperus difformis*	
9	*Nymphaea nouchali*	
10	*Marsilea quadrifolia*	
11	*Fimbristylis miliacea*	

Table 6. Critical period of weed infestation in rice culture.

Season	Critical period (day) of weed infestation in rice	
	Direct seeded rice (DAS)	Transplanted rice (DAT)
Aus	30-35	30-35
Aman	45-50	35-40
Boro	55-75	40-45

Table 7. Integrated weed management to reduce rice yield loss due to weed infestation.

Cultural management	Mechanical control	Chemical control
• Use weed-free seed • Proper land preparation and practice stale seedbed technique • Water management • Manual weeding 2-3 times as needed. To avoid competition weed during 15, 30 and 45 DAT	• BRRI weeder (15 DAT) + 1 HW in 30-35 DAT • Power operated weeder + 1 HW in 30-35 DAT	• Use Pre/post-emergence herbicide • Herbicide fb 1HW (35-45 DAT) • Maintain safe use of right herbicide(s) with right time, right dose, right method and with proper protection

Source: Bhuiyan *et al*., 2018

Weed control during early growth stage

Weed control is critical after planting until the rice canopy is fully covered. Control methods vary depending on the rice ecosystem and planting method.

Weed control in transplanted rice

- Apply pre-emergence herbicide (e.g., pretilachlor or butachlor or bensulfuron methyl + acetachlor) fb 1HW if needed.
- If grass weeds are the main weed problem, apply early post-emergence herbicide (e.g., pyrazosulfuron ethyl, ethoxysulfuron, phenoxlum etc.) fb 1HW if needed.
- Do not allow soil surface to dry after transplanting. Keep the soil moist to saturated. Dry soil reduces the performance of pre-emergence herbicides.
- If herbicides have not been applied, or if weeds are emerging, it is required to use BRRI weeder to control weed seedlings that are at 3−4 leaf stages.
- In case of hand weeding it should be done properly at 15-18 DAT(1st weeding), 30-35 DAT(2nd weeding) and at 40-45 DAT(3rd weeding) besides timely until rice is fully covered by a canopy.If weed competetion is low then weeding twice at 15-18 DAT and at 40-45 DAT.
- Rice crops must be kept weed-free by any method up to 30-45 DAT to get optimum yield.

Weed control indirect wet seeded rice by broadcasting/drum seeding

- Apply pre-emergence herbicide (e.g., pretilachlor + fenclorim 2−3 DAS or post-emergence e.g. Pyrazosulfuron ethyl at 10-12 DAS).
- For post-emergence herbicide application, drain water in the field to expose weeds, then spray herbicide. (Note: Post-emergence herbicide should come in contact with leaves of weeds to be absorbed by the weeds. When weeds are submerged in water, post-emergence will not be effective).
- Do not allow the soil surface to dry after seeding. Flush irrigate as needed to keep the soil moist to saturated. A dried soil surface will reduce the performance of pre-emergence herbicides.
- If herbicides have not been applied, or if weeds are emerging, may use BRRI weeder in a row-seeded crop to control weed seedlings that are at 3−4 leaf stages.
- Irrigate one day later to prevent buried and uprooted weeds from recovering.
- Hand weed as needed until rice canopy is covered.

Weed control in dry seeded rice

- A weed-free field is essential for early vigour in a dry-seeded rice crop. Be sure to follow steps for weed control during land preparation to avoid yield loss to weeds.

- Apply pre-emergence herbicide (e.g., oxadiazon, pendimethalin or oxadiargyl) in moist soil during 2−3 DAS. If the seed is sown on dry soil, flush irrigate the field first then spray the herbicide. Pendimethalin works well in dry soil.

- Post-emergence herbicides like Bispyribac sodium SC or penoxulam 240SC could be used at 20 DAE.
- If herbicide is not used to control weeds, hand weeding is required to control weed pressure.

Cultural Management for weed control

Cultural weed control includes non-chemical crop management practices ranging from variety selection to land preparation to harvesting and postharvest seed processing. Cultural weed control is a part of integrated weed management which involves the integrated use of cultural, manual, and/or mechanical control methods. It is easy to practice, acceptable, and accessible to small and large farmers as well as non-chemical and ecologically sound.

How to use cultural practices to control weeds?

- **Timing.** Weeds need to be controlled from planting until the rice canopy closes.
- **Land preparation and leveling.** Use land preparation to control growing weeds and to allow weed seeds to germinate. Kill newly emerging weeds by repeating tillage at adequate intervals.
- **Reduce weed entry into fields.** Prevent the introduction of weeds into fields by: i) using clean good quality seed, ii) keeping seedling nurseries free of weeds to make sure weeds are not planted with the rice seedlings, iii) keeping irrigation channels and field bunds free of weeds to prevent weed seeds or vegetative parts entering the fields iv) using clean equipment to prevent field/crop contamination and v) rotate crops to break weed cycles.
- **Fallow management.** Destroy weeds in fallow fields (e.g., use tillage) to prevent flowering, seed-set and the build-up of weed seeds in the soil (Should remember: "one year of seeds, seven years of weeds").
- **Crop-weed competition.** Select a weed-competitive variety with early seedling vigor, and high tillering to suppress weeds. Transplanted crops tend to have fewer weeds and less yield loss than direct-seeded crops. Transplant healthy, vigorous seedlings that can better compete with weeds in the early stages. Maintain an adequate plant population that closes its canopy by maximum tillering to shade out weeds. Apply Nitrogen (N) fertilizer just after weeding to minimize rice-weed competition for N.
- **Water management.** Water is the best control for weeds. Many weeds cannot germinate or grow under flooded conditions (e.g. most grasses and some sedges). Flooding is effective against many weed species but some species such as *Sphenochloa zeylanica, Monochoria vaginalis* and *Cyperus difformis* are not controlled by flooding.Maintain a 2-5 cm water level in the field to minimize weed emergence and lower weed pressure. If water is sufficient, fields can be continuously flooded from the time of transplanting to when the crop canopy covers the soil completely.

Mechanical weed control

Mechanical weeding is a part of integrated weed management that refers to the integrated use of cultural, manual, mechanical and/or chemical control methods. Mechanical weeding is preferable because it is non-chemical and ecologically sound, less labour needed and costs less than hand weeding and less drudgery than in hand weeding. BRRI power weeder (BPW) and BRRI weeder (BW) reduced weeding cost, enhanced weed control and improved the labour efficiency without sacrificing grain yield with the highest BCR obtained in BPW (1.22) followed by BW (1.16) and HW (1.11). BPW and BW appeared to be economic, easy and also environmentally safe weed control devices in low land rice cultivation (Islam *et al.,* 2017). But they have some limitations of mechanical weeding, such as:

- Only suitable for row-planted crops.
- Difficult in hardened soil or where water is limited.
- Difficult to remove weeds within crop rows.
- Only effective with young weeds (2- to 4 leaf stage).

How to apply mechanical weeder effectively?

- With 2-3 cm of water in the field, start using a weeder when emerged weeds are young (3 to 4 leaf stage).
- Remove the weeds near the plants by hand.
- Ten decimal lands could be weeding by one hour with one man.

Mechanical weeding

Manual weed control

Manual weeding is preferable because it is non-chemical; ecologically sound, Provides clean and thorough weeding, and good for resource-poor farmers where labor is available at low wages.

Limitations of hand weeding

- Labour-intensive, time-consuming and costly and high drudgery with stress on labour.
- Difficult if the soil surface is not moist and loose.
- Difficulty in identifying and removing certain grassy weeds at early stages (e.g. weedy rice, *Echinochloa spp*.). Have to remove such weeds from the field at flowering time.
- Weeds may survive if pulled and dropped into standing water.

Hand weeding: How to do it effectively and timely

- Weeds need to be controlled from planting until the crop canopy closes.
- Start hand weeding within 15 days of planting (or when weeds are large enough to grasp).
- Repeat the weeding once or twice more at 30-35 and 40-50 days after transplanting (DAT) or 40-45 and 55-75 days after sowing (DAS).
- Do not allow weeds to flower and set seeds in a crop field.
- Use good land leveling to reduce weeds.

Chemical weed control

In chemical weed control, chemicals called herbicides are used to kill certain plants or inhibit their growth.Chemical weed control is an option in integrated weed management that refers to the integrated use of cultural, manual, mechanical and/or chemical control methods.

Hand weeding

Classification of herbicide

Based on time of application, herbicides are classified as

- ***Preplant.*** Preplant herbicides are applied before the crop is planted. They are usually used to kill weeds that have germinated before planting or were left from fallowing. Glyphosate and paraquat is the example of a pre-plant herbicide. glyphosate or paraquat could be use to kill fallow weeds before 8-10 DAT of rice. Only selective herbicide surfentrazone can be used as pre plant herbicide before 2/3 days of transplanting.
- ***Preemergence.*** Applied after the crop has been planted but before weeds emerge. Preemergence herbicides are usually applied to the soil surface. They are used to prevent the establishment of weeds right after planting. They must not be toxic to the crop. Butachlor, pretilachlor, mefeneset + bensulfuron methyl, bensulfuron methyl+ acetachlor is the example of a pre-emergence herbicide.
- ***Postemergence.*** Applied after weeds have emerged. Post-emergence herbicides are used to control weeds that have been established in the crop. They should not be toxic to the crop and usually must contact the weed foliage to be more effective. An example of a post - emergence herbicide is pyrozosulfuron ethyl, ethoxysulfuron, diafimoni, bensulfuron methyl+ quinchlor, bispyribac sodium SC, penoxulam 240 SC etc.

Based on mode of action, herbicides are classified into two

- ***Contact.*** Contact herbicides are applied to foliage and other above-ground parts of a plant. They kill plant tissues at or very close to the application site. An example of a contact herbicides are propanil, glyphosate, 2,4-dichlorophenoxyacetic acid (2,4-D)
- ***Translocated/Systemic.*** Translocated herbicides are absorbed by the roots or above-ground parts of a plant. Within the plant, the herbicides then move to and kill tissues that may be remote from the point of application but where herbicide action occurs.Translocated herbicide move to the site of action via the transport mechanisms within the plant; the xylem and phloem. The xylem transports water and nutrients from the soil to growth sites and the phloem transports products of photosynthesis (for instance, sugars) to growth and storage sites.

Based on selectivity

Selectivity is how narrowly or widely an herbicide is effective on plants and falls into two categories:

- ***Selective.*** A herbicide that kills or stunts some plant species with little or no injury to others, especially the crop, is selective. Examples of selective herbicides used in rice production are butachlor, propanil,bensulfuron methyl+acetachlor, ethoxysulfuron and 2,4-D. These herbicides do not kill rice and are therefore safe to use.
- ***Non-selective.*** A herbicide that kills all plant species, or shows no selectivity, is nonselective. An example of a nonselective herbicide is glyphosate and paraquat that kills all plants in a field, including rice.

How to use herbicides effectively to control weeds?

- Always read and follow the instructions on the product label.
- Ensure the product is suited for the type and stage of crop and weeds to be controlled.
- Ensure field conditions are suitable (e.g., some products only work when the soil is moist, or when there is standing water or no standing water).
- Products are designed for early application when weed control is most important. Some products are designed to control the weeds before they emerge (pre-emergence), while others are only effective after the weeds have emerged (post-emergence).
- Use the recommended rate of fresh and clean water.
- Uniformly apply herbicide across the field.
- Spray herbicide from a height of around 50 cm above the target.
- Minimize movement of the herbicide to non-target areas by using low pressures, avoiding applications in very strong winds, and by limiting water run-off from fields.
- Spray perpendicular across the wind, so that product is blown away from the applicator.
- Be sure to rotate the usage of herbicides so weeds do not develop resistance.

Limitations of chemical weed control

- Herbicides are toxic substances, if those are used unwisely or incorrectly can cause health and environmental problems.
- Herbicides are often weed-specific.
- Weeds can develop herbicide resistant if farmers are too reliant on one type of herbicide.
- Drift risk to neighbor crops.
- Applicators require skills in application and calibration.

Safety consideration

- Always wear protective equipment. Use appropriate cover for head, eyes, nose, mouth, and hands. Wear long-sleeved shirts, long pants, and covered footwear.
- When mixing the product, always stand upwind and wear protective clothing – especially face protection.
- Wash contaminated clothes separately from other household clothes.

Note

- At recommended doses, a herbicide may be selective when used with a particular crop.
- However, if higher doses are used or if the herbicide is applied at the wrong time, it can damage or even kill the crop.
- The same herbicide may be selective or nonselective, depending on the rate and time of application.

Residual effect of herbicide

According to World health organization (WHO) "any substance or mixture of substances in food for man or animals resulting from the use of a pesticide and includes any specified derivatives, such as degradation and conversion products, metabolites, reaction products, and impurities that are considered to be of toxicological significance" are defined as herbicide/ pesticide residues.

Herbicide is gaining popularity in rice cultivation due to its low cost, high efficacy, and timely control of weeds. In Bangladesh, the annual consumption of herbicides grew over 7400 metric tons in 2019 (BCPA, 2020) compared to only 108 tons during 1986-87 (BBS, 1991), and the growth is almost exponential (Fig. 3). Pyrazosulfuron ethyl, mefeneset+ bensulfuran methyl, mefeneset + acetochlor, bispyribac sodium, oxadiazone, pretilachlor, butachlor, ethoxysulfuran, oxadiarzil, 2,4-D, etc. are the commonly used herbicides in rice cultivation in Bangladesh (Table 8). Data indicated that the use of herbicide will be considerably increased in near future for rice cultivation. Incorrect and indiscriminate application of herbicides affects negatively the health of humans, plants and animals. Particularly hazardous are the poorly degradable herbicides whose persistence may lead to long-term accumulation.

Soil microorganisms are an important link in the soil-plant system. Herbicides can contaminate soil, water, turf, and other vegetation. Insecticides are generally the most acutely toxic class of pesticides, but herbicides can also pose risks to non-target organisms. Herbicide sometimes contaminates the surface and groundwater. Some herbicides show phytotoxicity to the rice plant. Moreover, the question arises frequently from different corners, especially from the environmentalists about the effect of herbicide on the environment along with soil and water. The policymakers also want to know its safe use and residual influence on soil and crop. Some herbicides may take a long time to disintegrate, may adversely affect the soil health and groundwater. Herbicide residue may persist in straw and grain. Although herbicide is less toxic than insecticides, even the information regarding its persistence in soil and crop plant is lacking in Bangladesh.But studied from India demonastred that at harvest, herbicides in various commodities and different families were found either below the maximum residue limit or below detectable limits in grain and straw (Sondhia ,2014). Herbicide residues after recommended use for control of weeds are relatively high initially; however, the levels are reduced rapidly, and residues are often not detectable after a few days or weeks or at harvest (Sondhia ,2014). Nevertheless,Farmers should be informed about the influence of herbicides on the soil and crop. Furthermore, herbicide residue persistence on soil and crop if any needs to be carefully studied in Bangladesh condition.

Microbiological effects of herbicides were studied at BRRI (BRRI, 2015-16). Higher concentrations of herbicide treatments resulted in much lower microbial counts compared to soils treated with recommended herbicide dose. But in general, all bacterial and fungal populations were reduced three days after herbicide application (DAHA) and the population increased 7-20 DAHA and thereafter microbial population fluctuated over time. So the application of herbicide in soil reduced soil microorganisms in a certain time and after 7-20 days, it becomes increased than before.

Therefore, we need clear understanding of herbicide residue in soil and crop plants for safe food grain consumption. As the SDG 2 and BDP (Bangladesh Delta Plan) 2100, Volume 4 baseline study indicated, we have to produce and ensured safe food and nutrition.

Table 8. The herbicide used in Bangladesh are listed with chemical/common name and effective dose with remarks.

Chemical	Effective dose/ha	Time of application	Remark
Oxadiazon	1.0 L (DSR) 2.0 L (TPR)	3-5 DAS/DAT	Direct dry/wet seeded and transplanted rice. Effective for sedges, broadleaves and some grasses. Works best with standing water or at least moist soil. Soil must remain moist after application to maintain activity.
Butachlor	25 kg	3-5 DAT	Pre-emergence, effective for grasses, some broadleaves and sedges
Carfentrazone ethyl	62.5 g	20-22 DAT	Post emergence, effective for broadleaf
Pretilachlor	1.0 L	3-5 DAT	Pre-emergence, effective for grasses, some broadleaves and sedges
Pretilachlor+safener	1.0 L	3-5 DAS/DAT	DSR, effective for grass, sedge and broadleaves
Pyrazosulfuron ethyl	125-150 g	10-12 DAS/DAT	Early post-emergence, sedges and broadleaves, few grasses
Ethoxysulfuran	100 g	10-12 DAS/DAT	Early post-emergence.Effective for sedges and broadleaves
Glyphosate	4-5 L	Pre plant	Pre-plant, deep-rooted perennial weeds and annual grasses, sedges, and broadleaves.
Paraquate	2.0 L	Pre-plant	Pre-plant, suppress weed dry mass.
MCPA	1.0 L	25-28 DAT	Post emergence, effective for wide ranges of weed
Oxadiarzyl	188 ml	3-5 DAS/DAT	Preemergence, effective for dry and wet seeded rice. Spray without standing water in the field.
2,4 D - Amine	1125 g	20-25 DAS/DAT	Post-emergence, effective for broadleaves and annual sedges. Weeds need to be above the waterline.
2,4 D butyl ester	1.8 kg	20-25 DAS/DAT	Post-emergence, effective for broadleaves and annual sedges. Weeds need to be above the water line.
2,4 D			Pre-plant
Pendamethalin	2.0 L	3-5 DAS/DAT	Preemergence, effective for dry seeded rice. Effective for Echinochloa spp., some annual grasses, sedges, and broadleaves. Need residual moisture for activating.
Mefenacet+Bensulfuron methyl	1111 g	3-5 DAT	Pre emergence, effective for all weeds
Bensulfuron methyl + Acetachlor	750 g	3-5 DAT	Pre emergence, effective for all weeds
Butachlor+Propernil	1.0 L	3-12 DAS/DAT	Pre and post-emergence, effective for sedge and broadleaves, some grasses. Apply on saturated soil, flood field 1-3 DAA; spray volume is 200 L/ha
Pyrazosulfuron ethyl+pretilachlor	800 g	3-15 DAT	Pre and post-emergence, effective for sedge and broadleaves, some grasses
Bispyrabyc Sodium	125-150 g	8-16 DAS/ DAT	Post-emergence, effective for grasses (especially Shama) some BL and S. Drain excess water before spraying for target weeds to appear one-half part over the water surface and re-irrigate during 1-3 DAA.
Oxylfluorfen	1.0 L	3-5 DAT	Pre emergence
Bensulfuron methyl+queenchlore	600 g	3-15 DAT	Pre and post emergence
Acetachlor	250 ml	3-5 DAT	Pre emergence
Cylophop-butyle	100 ml	15 DAT	Post emergence, only annual grasses
Bispyribac sodium+bensulfuron methyl	142.5 g	10-12 DAT	Post emergence; grass, sedge and broadleaves
Bensulfuron methyl 10%+Chlorimuron ethyl 10%	20g	12-15 DAT	Post emergence; grass, sedge and broadleaves
Metolachlor+ Bensulfuron methyl 20%	190ml	3-6 DAT	Pre emergence, grass, sedge and broadleaves
Sulfentrazone 48SC	200ml	Before 3 days of TP and upto 3DAT	Pre plant and pre emergence herbicide
Fenxo-prop-P- ethyl	500 ml	3-5 DAT	Pre emergence, grasses
Diafimoni 200SC	190ml	12-15 DAT (1-3 leaves)	Post emergence; all weeds

Productivity could be increased using herbicides

Due to shortage of labour in peak period and the higher cost of hand weeding, herbicide use is increasing every year in Bangladesh. The trend of herbicide use (BCPA, 2019) up to 2018 (Fig. 2) indicates that in the future herbicide use will increase sharply and labour productivity will also be increased. Research in Bangladesh demonstrated that herbicide applications would produce similar rice yields to three carefully timed hand weeding with a significant reduction in labour requirements and total costs. Pre-emergence herbicides are 38-46% cheaper than one hand weeding (Mazid *et al*., 2001).

Economic analysis of rice production in Bangladesh revealed that the net income from herbicide application was 116% higher than three times hand weeding (Rashid, 2012). Herbicide use reduced weed control time to a mean of 84 hours ha^{-1} compared to 590 hours ha^{-1} in rice for which at least two hand weedings were needed (Mazid *et al.,* 2006). Using herbicide instead of manual weeding 85% of labour can be saved. Therefore, rice productivity can be improved through the effective use of herbicides by significantly reduce labour. Bhuiyan *et al.,* (2018) reported that weed control efficiency of commonly available herbicide in Bangladesh were more than 80% and save about 6000-7000 Taka ha^{-1} compared to thrice hand weeding. In farmers field, 61% of the cost was reduced due to herbicide use whereas, 49% of the cost was reduced when used BRRI weeder + 1HW for weed management of rice (Table 9).

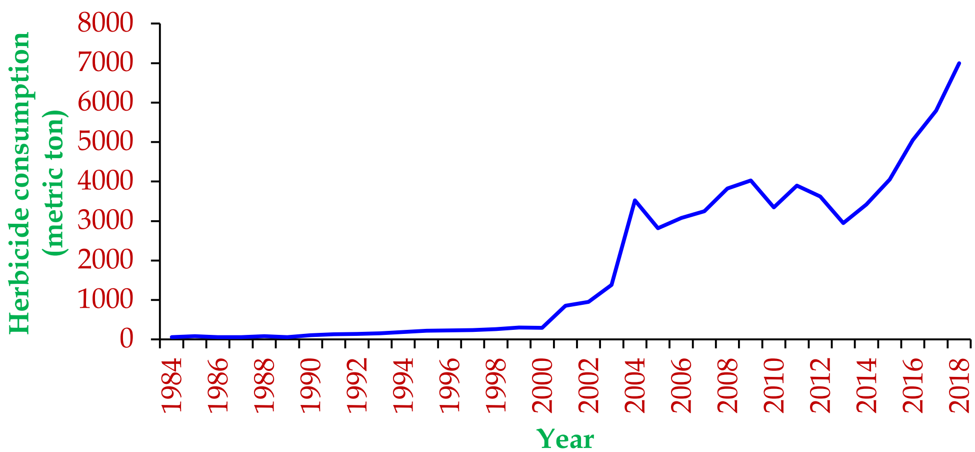


Fig. 2. Herbicide consumption in Bangladesh during 1984 to 2018.

Source: Bhuiyan *et al.*, 2018

Table 9. Weed management cost reduction by using BRRI developed technology in Pirojpur, Gopalganj and Bagerhat district during 2016.

Weed management treatment	Grain yield (t ha^{-1})		Weed management cost (Tk ha^{-1})		Cost reduced over FP	
	Aman	Boro	Aman	Boro	Aman	Boro
Farmers practice	4.95	6.50	12600	14400	-	-
Herbicide fb 1HW	5.24	6.95	4750	5550	62	61
BRRI weeder fb 1HW	5.10	6.64	6450	7250	49	50

***fb 1 HW= Followed by 1 hand weeding**

Ecologically sustainable integrated weed management (ESIWM)

Integrated weed control utilizes direct and indirect means for cost-effective weed control or considering economic threshold level (Fig. 3). The essential feature of an integrated weed management programme is a critical blend of weed control methods that can be combined economically in a given situation. The contribution of indirect methods on a short and long-term basis and their cost-benefit ratio are needed to be considered for integrated weed management.

For example, increased frequency of plowing and laddering will not completely remove weeds from the crop field. So, a farmer has to employ a direct weeding method for increased production.

Therefore, the frequency of land preparation and laddering should be reduced to a minimum level in which crop establishment is not hampered and then direct weeding should be done in time for reducing crop-weed competition. A high seed rate can not substitute for direct weed control. It is also not economical to add more fertilizer without controlling weeds. Fertilizer efficiency is high when weeds are controlled. Therefore, maximum crop yield at minimum cost should determine the relative choice of integrated weed control. So integrated weed management is the solution.

Some salient features for integrated weed control are given below:

- Crop seed should be free of weed seed. It decreases the severity of weed infestation.
- Weed gets less favourable conditions to grow if the land is prepared well.
- In some cases, a few weeds are found to grow after applying herbicide. It should be controlled by hand or applying post-emergence herbicide.
- Use of weeders is friendly to the ecosystem. But one additional hand weeding is required.
- In transplanted rice proper water management reduces the infestation of weed.
- Use of weed competitive variety or allelopathic variety is another option of integrated weed management.

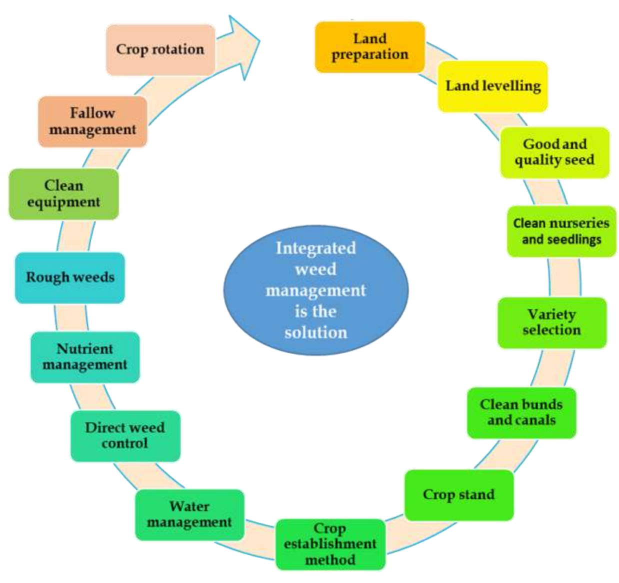


Fig. 3. Integrated weed management in rice production.

Synthesis of Ecologically sustainable integrated weed management(ESIWM) options

Herbicides remain a simple and cost-effective way to control weeds, as herbicide growth is increasing in Bangladesh, rice productivity can be increased through the judicious and safe use of the herbicide. Non-chemical weed control techniques may become important in the future where environmental safety is a major concern for chemical use. Mechanical weed control should be popularized all over the country where 50% of weeding cost could be minimized. An integrated weed management system along with other agronomic weed control methods could be followed in the future, e.g., the use of weed competitive variety, bioherbicide allelopathic variety, crop density manipulation, or tillage could be done for ESIWM. Table 10 recapitulate the strengths and weaknesses of the technologies, tools, and highlights for future research needs.

Major issues of weed management to be implemented with related approaches

The challenge for weed scientists is to develop innovative, effective, economical, and environmentally safe IWM systems that can be integrated into current and future cropping systems to bring a more diverse and integrated approach to weed management. For sustainable and ecologically friendly weed management by 2030 and beyond following major issues and related approaches to be implemented step by step (Table 11).

Table 10. Strength, weakness and research need for integrated weed management.

Method	Technology	Strength	Weakness	Research need	Recommendation
Hand weeding	Hand weeding twice or thrice	Effective weed control, Easy	Need more labor and cost; Timely weeding is not done	-	Could be included in integrated weed management (IWM)
Mechanical weed control	BRRI weeder fb 1HW	Effective weed control and reduces hand weeding and herbicide use; Reduces labour cost	Weeder not available all over the country	Massive validation and demonstration programme in all upazillas of Bangladesh	More effective mechanical weeder (manual/ power weeder) needed Part of IWM
Herbicide	Pre or post-emergence herbicide fb 1HW	Effective and timely weed control. Saves 80% labor and time. Reduces cost of cultivation	Right herbicide is not available in all areas. Safe use of herbicide and environmental pollution for chemicals is a concern	Evaluate new molecule herbicides and facilitate for commercial availability Optimizing dose and time of application and elucidating factors affecting efficiency; Integrate with other methods to reduce dose and increase efficiency; Long term effect of herbicides on weed dynamics, soil microflora, non-targeted organisms and herbicide residues in different crops and cropping systems	Research programme should be strengthened on the residual effect of herbicide and judicious use of the herbicide
Allelopathy	Allelopathic variety	Enhances crop competitiveness	Difficulty in isolating allelochemical compound	Breed cultivars with allelopathic potential	Part of IWM. Research work is ongoing to find out allelopathic variety and allelochemicals

Method	Technology	Strength	Weakness	Research need	Recommendation
Weed seed control	Long term weed control method	Depletion of weed from soil seed bank	Understanding weed seed retention at crop harvest	Long term experiment in different soil layer need to be conducted	Research work was initiated.It will be continued as it is a part of IWM
Bioherbicide	Yet to be developed	Environmentally benign	Difficulties in scaling up the production process	More emphasis should be given on biological control of weed	Part of IWM
Novel technologies	Nanotechnology. Yet to be develop	Could increase the precision and effectiveness of the natural herbicidal compounds delivery	New area of research. Effort to be done for formulation this issues	Innovation of nano-technology for herbicide and effectiveness of natural herbicidal compounds	We are so far from this technology. Research needs for nano-technology of weed control
	Image processing and remote sensing.	Detect weed patches,and consequently weed density mapping	May detect problems due to plant residues	New area of research. Could be done with remote sensing, automated detection and artificial intellegence.	Integrated geostatistics and remote sensing may facilitate intra-row weeding in the near future

Table 11. Major issues of weed management with connected approaches.

Major issue to be implemented	Related approach
Development and practice ecologically and sustainable integrated weed management	• Develop and disseminate guidelines for incorporating the nonchemical methods (cultural/mechanical and agronomic manipulation) with chemical methods in the farmers field • Reduce herbicide use by employing non-chemical methods • Develop and disseminate organic weed management practices. • Use crop residues as mulch material for suppressing weed
Managing weeds through judicious use of herbicides	• Evaluate new molecule herbicides which is more environmentally sound • Optimize their time and dose of application and elucidating factors affecting their efficiency • Integrate with other methods to reduce the dose and increase efficiency. • Quantify herbicide residue in soil, water and plant parts and consequent entry in the food chain • Find out long term effect of herbicides on weed dynamics, soil microflora, non-targeted organisms and herbicide residues in different crops and cropping systems
Developing bio-control measures for managing weeds	• Explore the potential pathogens, insects, fish, allelochemicals for utilization as biotic agents for weed management • Identification, evaluation and commercialization of plant/ soil pathogen/ microbes for biological control of major weeds
Facilitating dissemination of weed management technologies, knowledge and information	• Conduct training programmes, activities for different stakeholders • Increase interaction with farmers and stakeholders through direct approaches • Test and fine-tune of site-specific weed management technologies
Developing weed database in rice	• Create national weed database in different districts in Bangladesh to formulate suitable and sustainable weed management strategies

Action plan for three decades on reducing yield loss from rice weeds

To reduce yield loss from weed we have thoroughly discussed available methods of weed management strategies to be implemented. Since herbicide use is increasing due to its effectiveness and cost-effectiveness, so we have to judicially use herbicide. Moreover, not a single method is effective to control weeds in the rice field.

Therefore we have to integrate all methods intelligently. Ecologically sustainable integrated weed management (ESIWM) is the option to manage weeds and to reduce loss from weeds. However, an action plan was developed where all possible weed management options have been addressed.

During the research and development phase (Table 12a, Appendices 2 and 3) cultural, chemical and mechanical weed control will continue with framework development (FWD), yield loss assessment, calibration, and validation of smart management in the specific domain. This work will be followed up and continued.

A number of dissemination and training programme will be done in the farmers' field and concerned agricultural personnel, dealers will be trained regarding herbicide and its safe uses. In the meantime, weed control research with bioherbicide and allelopathic variety will be carried out. As a result, identification of biocontrol agents and allelopathic variety will be identified.

For the period of 2031-2040 and 2041-2050 (Tables 12b, 12c) all possible weed management options will be followed up and continued. If any of the methods will not work it will again go for calibration and validation and this process will continue. Ultimately farmers have to follow integrated weed management with the concerned of environmental issues (Fig. 4). Whatever management is applicable it should be ecologically sound and sustainable.

Table 12. Implementation of ecologically sustainable integrated weed management for the period of 2021-2030, 2031-2040 and 2041-2050.

a) Period 2021-2030

Ecologically sustainable integrated weed management (ESIWM)								
Period: 2021-2030								
Weed management option	Research and development Phase						Dissemination phase	
	Primary		Intermediate	Maturation		Follow up	Step-1	Step-2
	III	YL-EST	Mtg - FWK	Cali-Valid	Sm - Mtg	CO	Train	Demo
CWM1								
CWM2								
CWM3								
CWM4								
CWM5								
CWM6								
MWM1								
MWM2								
HWM1								
HWM2								
HWM3								
BWM1								
BWM2								
AWM1								

b) Period 2031-2040

Ecologically sustainable integrated weed management (ESIWM)								
Period: 2031-2040								
Weed management option	Research and development Phase						Dissemination phase	
	Primary		Intermediate	Maturation		Follow up	Step-1	Step-2
	III	YL-EST	Mtg-FWK	Cali-Valid	Sm-Mtg	CO	Train	Demo
CWM1								
CWM2								
CWM3								
CWM4								
CWM5								
CWM6								
MWM1								
MWM2								
HWM1								
HWM2								
HWM3								
BWM1								
BWM2								
AWM1								

c) Period 2041-2050

Ecologically sustainable integrated weed management (ESIWM)								
Period: 2041-2050								
Weed management option	Research and development Phase						Dissemination phase	
	Primary		Intermediate	Maturation		Follow up	Step-1	Step-2
	III	YL-EST	Mtg - FWK	Cali-Valid	Sm-Mtg	CO	Train	Demo
CWM1								
CWM2								
CWM3								
CWM4								
CWM5								
CWM6								
MWM1								
MWM2								
HWM1								
HWM2								
HWM3								
BWM1								
BWM2								
AWM1								

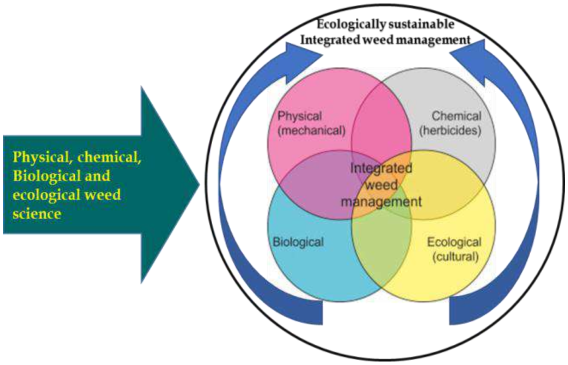


Fig. 4. Ecologically sustainable integrated weed management (Adopted and modified from Merfield CN, 2019).

CONCLUSION

Hand weeding and chemical weeding are generally very much popular in Bangladesh. Herbicides may now find greater acceptance by the farmers due to higher wages and unavailability of labour. Herbicide producers and weed scientists have an enormous responsibility to educating the farmers and the extension personnel on the judicious and sustainable use of herbicides. The research related to herbicides must go beyond herbicide screening to application techniques, enhancing herbicide efficiency and integrating with ecological methods of weed management. The basic research on weed biology, weed seed bank, bioherbicide, weed ecology and weed control by the tools of remote sensing and geostatistics which has been largely ignored until now needs encouragement. Research on mechanical and biological weed control should get more attention of the researcher to serve the farming community for sustainable food production to achieve sustainable development goals.

RECOMMENDATIONS

- Developing and upscaling economic and eco-friendly weed management technologies emphasizing mechanical and biological weed control which strengthen the ecologically sustainable integrated weed management (ESIWM) system.
- Non-chemical weed control research should be strengthened. Allelopathic and bioherbicide research may provide non-chemical weed control technology for different crops.
- A nationwide weed survey programme on rice fields and rice based cropping system may be initiated to identify harmful weeds in the climate change situation.

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AUTHORS' CONTRIBUTION

MKAB generated idea; MUS and MSK coordinated the research; MKAB developed methodology, provided scientific insights, gathered data, carried out analysis and synthesis, and did the writings for all versions of the manuscript; MUS and MSK performed critical review and editing. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

A version of the paper was published in a book "Doubling Rice Productivity in Bangladesh" in 2020 by the Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh to commemorate BRRI's 50th anniversary. The Bangladesh Rice Journal has prior knowledge of the book publication and does not see any conflict of interest.

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Acronyms and Abbreviations

BRRI= Bangladesh Rice Research Institute
IWM= Integrated Weed Management
BINA= Bangladesh Institute of Nuclear Agriculture
IRRI= International Rice Research Institute
GO = Government organization
IPM = Integrated pest management
NGO = Non-government organization
SDG = Sustainable development goal
CIMMYT= The International Maize and Wheat Improvement Center
G= Granular formulation
DAS= Days after sowing
DAT= Days after transplanting
DAP= Days after planting
SDR= Sum Dominance Ratio
FB= Followed by
AI= active ingredient
EC= Emulsifiable concentrate
SC= Soluble concentrate
BPW= BRRI power weeder
BW= BRRI weeder
HW = Hand weeding
BBS= Bangladesh Bureau of Statistics
DAHA= Days after herbicide application
ESIWM= Ecologically sustainable integrated weed management

Appendix 1a. Photograph of low land weeds commonly found in rice field.

Echinochloa crus-galli

Monochoria vagianalis

Cyperus difformis

Scirpus maritimus

Cyperus iria

Fimbristylis miliacea

Ludwigia octovalvis

Sphenoclea zeylanica

Paspalum distichum

Appendix 1b. Photograph of up land weeds commonly found in rice field.

Echinochloa colona

Cyperus rotundus

Cynodon dactylon

Elusine indica

Dactyloctenium aegyptium

Digitaria sanguinalis

Eclipta allba

Imperata cylindrica

Amaranthus spinosus

Commelina diffusa

Appendix 2. Weed management at a glance with abbreviation.

Broad weed management	Weed management option	Abbreviation
Cultural	i. Fallow management	CWM1
	ii. Good land preparation & Stale seedbed technique	CWM2
	iii. Planting method and plant population	CWM3
	iv. Crop rotation	CWM4
	v. Water mgt- Flooding	CWM5
	vi. Weed competitive variety	CWM6
Physical	i. Manual weeding	MWM1
	ii. Mechanical weeding	MWM2
Chemical	i. Pre emergence herbicide	HWM1
	ii. Post emergence herbicide	HWM2
	iii. Pre plant herbicide	HWM3
Biological	i. Rice duck culture	BWM1
	ii. Bioherbicide	BWM2
Biochemical	i. Allelopathic variety	AWM1

Note: CWM= Cultural weed management; MWM= Mechanical weed management; HWM= Herbicide weed management; BWM= Biological weed management; AWM= Allelophathic weed management

Appendix 3. Some abbreviation with elaboration in relation to Tables 12a, 12b and 12c.

Programme	Phase	Abbreviation	Elaboration
Research and Development	Primary	III	Identification, isolation and innoculation
		YL-EST	Yield loss estimation
	Intermediate	Mtg-FWK	Management framework
	Maturation	Cali-Valid	Calibration and validation
		Sm-Mtg	Smart management
	Follow up	CO	Continuous obervation
Dissemination	Step-1	Train	Training
	Step-2	Demo	Demonstration

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Agronomic Management and Interventions to Increase Rice Yield in Bangladesh

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ABSTRACT

Avenues of agronomic manipulation need to be explored critically for getting potential rice yield in a given environment. Increasing population, decreasing resources and increasing climate vulnerability such as salinity, drought, submergence, early flash flood in ha or areas can interrupt achieving the target of rice yield. Location specific variety, profitable cropping sequences, innovative and smart cultural management, and appropriate agronomic management with smart dissemination using multiple means would maximize rice yield and decrease the production barriers of rice. Appropriate variety and location-specific crop management systems should be formulated for rice yield maximization to reduce yield gap in farmers' field. A number of approaches can be undertaken for maximizing rice yield by adopting location-specific crop production e.g., manipulating sowing and planting times, appropriate weed management technology in proper time, suitable variety selection for improving cropping intensity, Judicious and balance application of organic and inorganic fertilizer application etc. Nitrogen application before panicle primordia is crucial because at this stage panicle primordia determined the spikelet number of the panicle and the absorbed nitrogen is efficiently used to increase spikelet number, accumulated photosynthates to leaf sheath and culm and, hence, increases panicle size and grain yield. Farmers should have a plan and should follow different steps of rice production to get higher yield and sustain productivity. Rice growth stage-wise agronomic management should be followed to get maximum yield. Choice of appropriate variety in a specific location or ecosystem is a major concern that contributed about 20% to the grain yield. Whereas management is a big issues which contributed about 60% for obtaining higher grain yield.The difference of environment × management explained the largest variations (80%) in explaining the yield. The bridging of knowledge gaps can bridge yield gaps. New paradigms need to be added to transfer and use new high yielding varieties and knowledge based technologies under new policy settings.

Key words: Rice production, yield gap, agronomic management

INTRODUCTION

The almost uneven topography and humid tropical climate of the country with abundant monsoon rain offer a unique environment for the rice plant in Bangladesh. The rice-growing environment of the country has been classified into three major ecosystems based on physiography and land types. These are a) irrigated b) rainfed, and c) floating or deepwater ecosystems. The rainfed ecosystem has been further classified as rainfed lowland and rainfed upland. Thus, all rice varieties cultivated in the country are grouped into five distinct ecotypes such as a) Boro, b) Transplanted Aus (T. Aus), c) Transplanted Aman (T. Aman), d) Upland Aus (direct seeded Aus), and e) Deepwater rice (Floating rice).Boro rice is grown completely under the irrigated ecosystem during the dry period (October/November to June/July) while T. Aman (July to December), T. Aus (during March/April to August) and Upland rice (March to July) are grown under the rainfed ecosystem to maintain the current production level and to feed the extra population in the future rice production(Fig 1.). Increasing rice production further is a gigantic task since there is no scope for horizontal expansion of the rice

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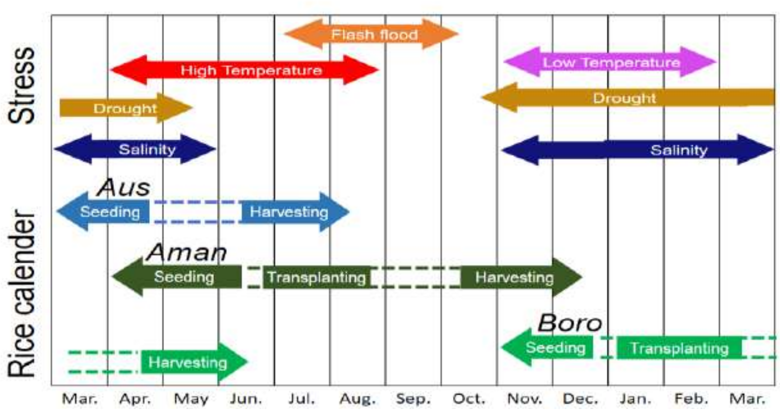
area due to the gradual diminishing of cultivated land as a result of diverting its uses for houses, roads, industries and urbanization (Sattar, 2000). We have to cope up with different stresses like salanity, submergence, drought, cold, high temperature and flsah flood manipulating and tailoring agronomic management to enable the rice farmers to adopt an uncertain future climate change based on research supported data by researchers and different stakeholders (Fig.1).

The population of Bangladesh will reach 215.4 million in 2050, when 44.6 MT (million ton) of clean rice will be required (Kabir *et al.*, 2015). Bangladesh is losing arable lands about 220 hectares per day, equivalent to 1% of the country's cultivable land per year. The government, therefore, considers food and nutrition security as a key means for the country's economic growth, with a view to becoming a middle income country by 2025. The yield gap of rice production is 0.83 tha^{-1} (20.7%) between actual farm yield and potential farm yield in Bangladesh (Kabir *et.al,* 2015). If this yield gap could be reduced @ 1.135% $year^{-1}$, 4.8 MT rice surplus can be achieved in 2050. Reducing the yield gap of 10-15 kg $year^{-1}$ ha^{-1} would provide a surplus of 3.07 MT in the year 2041(Kabir *et al.*, 2015).

Our vision is sustainable food, nutritional and livelihood security, and maintains rice production level to feed the increasing people of Bangladesh. Our mission is to develop and disseminate eco-friendly technologies to enhance the productivity, profitability, and sustainability of rice cultivation. Agronomy, a prime discipline in the field of agriculture, can play an important role in elevating and sustaining rice production in Bangladesh. According to rice vision (Kabir *et al.*, 2015), the current population of 162 million will rise to 171 million in 2021, near 200 million in 2030 and across 200 million in 2040, and reach 215 million in 2050. Accordingly, the production demand of clean rice will go up to 38.83 MT in 2031 which is 10% more compared to the current production level. Increasing rice production further is a gigantic task since there is no scope for horizontal expansion of the rice area due to the gradual diminishing of cultivated land as a result of diverting its uses for houses, roads, industries, and urbanization.Three interventions to be employed in order to maintain the current momentum of rice production in Bangladesh (Kabir *et al.*, 2015). These are: (i) accelerating genetic gain, (ii) minimizing yield gap, and (iii) curtailing adoption lag of rice varieties in the field.



Source: Adopted and modified from Shelley et. al.,2016

Fig. 1. Agroclimatic conditions and rice calendar of Bangladesh (The above block arrows indicate the different kinds of stresses induced by the agroclimatic parameters throughout the year and the lower block arrows with dashes represents the rice crop calendar of Bangladesh).

Specific input and agricultural management strategies are required to achieve the potential production by overcoming biophysical and socioeconomic constraints causing yield gaps (Pradhan *et al*., 2015). The management strategies include: fertilizers, pesticides, advanced soil management, land improvement, ecosystem based production management and improving market convenience for growers. Therefore, options available for increasing rice production are a) a breakthrough in the present yield potential of the varieties, b) full exploitation of the present yield potential of the existing modern varieties; and, c) utilization of unfavourable but potential ecosystems for rice and or other systems of food production (Sattar, 2000).

This paper will elaborate on the possibility and means of exploiting the yield potential of the existing modern rice varieties and problems as well as the way of minimizing of rice yield gap at the farmers' level.

With the above background, the article undertook three specific objectives in relation to specific agronomic management.

i. Presentation of changing status of different agronomic management practices

ii. Highlighting the scenarios of yield loss associated (projected and actual) with several agronomic management; and,

iii. Development and mapping the action plan for three decades on reducing yield loss from different agronomic management.

MATERIALS AND METHODS

Yield loss from different agronomic management practices was considered through a discussion meeting with a group of agronomists, statisticians, and other scientific personnel with the help of current secondary and reviewed data. It was assumed that realistic yield loss from different agronomic management (time of planting, seedling age, spacing, fertilizer, weed, transplanting depth, and others) was 15.35%. The projection was made from current status of rice production, yield loss due to improper management practices and minimization of yield loss up to 10%. It was reviewed from different experimental data that different agronomic management like use of aged seedling, inappropriate time of planting, spacing, imbalance fertilizer application, weed, seed quality and tillage may reduce a certain level of yield. Yield loss projection from different agronomic management was calculated from the baseline yield loss quantity. Table 1 presents the baseline yield loss data (Kabir *et al*., 2020).

Table 1. Yield loss (%) due to different agronomic factors.

Agronomic factor	Yield loss (%)
Time of sowing/transplanting	4.75
Seedling age	2.50
Spacing	1.20
Weeds	1.90
Fertilizer (dose and timing)	4.00
Other agronomy management (seed quality, tillage etc)	1.00
Total	15.35

Source: Adopted from Kabir *et al*., 2020

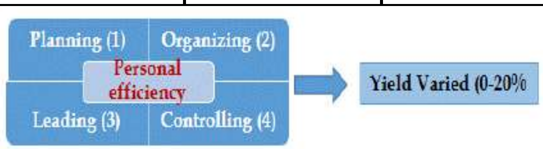
RESULTS AND DISCUSSION

Agronomy and its contribution in enhancing the yield

The ultimate goal of any farmer is to get maximum yield per unit area. The low yield on the farmer's field could be ascribed to the failure of the farmers to adopt and practice the recommended agronomic practices that govern the production of the crop. Table 2 shows the role of agronomic management in grain yield which is described by Salam *et al*., 2016. Choice of appropriate variety in a specific location or ecosystem is a major concern that contributed 20% to the grain yield. Whereas management is a big issue which contributed 60% for obtaining higher grain yield. However, it is the largest variation of environment × management that explained the largest variation (80%) in explaining the yield. The classical equation of yield is y = G × E × M × P……Eq. 1 (Salam *et* *al.*,2016). Where "G" is the genotype or variety of a crop and "E" is the environment on which the variety is set to express its potential(Eq.1). In recent years, the "E" component has been segregated to "E" by "M", where "M" is management.This segregation has been necessary because the whole atmosphere of the environment (E) is changed due to management (M). It has been added another component "P" to this equation(Eq.1). Here "P" stands for people and very simultaneously, management is run by the efficiency of people involved. For example; with the same prescribed management system, two fields sitting side by side can perform differently because of farmers' ("P") personal efficiency. Personal efficiency depends on timely planning, organizing the product materials, leading to distribute of inputs and control the farm from any kind of stress. The non-G component largely belongs to "Agronomy".

Table 2. Variety, management and environmental effect on yield of rice.

Component	Sub component	% yield depends
Genotype/ Variety(G)	-	20
Management(M)	Technical knowledge and Personal efficiency(P)	60
Environment(E)	-	20
Total	-	100%



Source: Adopted and modified from Salam *et al*., 2016

Generic yield loss management options

Management factors that pull down farm-level yield in different rice ecosystems in different growing seasons and plan for reduce yield

a. **Delay of sowing/transplanting.** Planting of rice becomes late resulting in a reduction of yield at the rate of 60.0, 55.4, and 9.6 kg ha^{-1} for each day delay during Boro, Aus, and Aman seasons, respectively (Table 3). Table 3 indicates projected yield loss (%) due to wrong sowing/transplanting time and minimization of yield loss with practicing recommended sowing/transplanting time.It is possible to add a significant amount of clean rice through maintaining timely sowing and transplanting.

Farmers often cannot follow the appropriate cropping system due to the shortage of draft power, unavailability of labor due to the sudden high demand during the peak period when farm activities overlap across the seasons. Time of planting, optimum seedling age, seeding time, and transplanting time should be maintained properly based on season, ecosystem, and growth duration of rice varieties. Otherwise significant yield loss will have occurred.

Because of the delay in Boro, the crop may face an early/flash flood and may be damaged. If delay in Aman, the yield will be decreased due to incomplete vegetative growth, in the immaturity stage and variety may fall in cold and sterility may be increased. If delay in Aus, Aman will be delayed and the yield will be decreased. If early in Aman, pest infestation will be high and yield will be decreased. If early in Aus, it will be in high temperature and sterility. If early in Boro, it will be in low temperature and sterility. So optimum and recommended planting time with optimum seedling age is a prerequisite to get a higher yield. Table 4 and 5 present seasons and ecosystem-based recommended seeding and transplanting time and seedling age.

b. **Use of unhealthy seed.** Poor quality seeds produce unhealthy plants resulted in poor growth and development and decrease grain yield.Using cleaned and quality rice seeds increased grain yield, enhanced crop growth, and also reduced damage from weeds, insect pests, and diseases.

Table 3. Yield reduction due to increased seedling age.

Season	Recommended seedling age (day)	Yield reduction with the increase of seedling age (kg ha^{-1} day^{-1})
Boro (normal)	40-45	24-40
Boro (cooler areas)	50-55	2-125
T. Aus	15-30	1-37
T. Aman (normal)	30	2-77
T. Aman (late and very late)	45-50	1 to more than 71

Source: Ahmed *et al.*, 2006: BRRI-DAE technology transfer workshop paper (2006)

Table 4. Season wise and ecosystem-based seeding, transplanting and seedling age of rice in Boro and Aus seasons.

Season	Ecosystem	Agricultural region	Appropriate seeding time		Seedling age (day)
			Short duration variety	Long duration variety	
Boro	Favourable	All region	15-21 Nov	1-7 Nov	35-45
	Haor region	Kishoreganj, Netrakona, Sylhet, Sunamganj, Habiganj, B. Baria and Moulavibazar	15-21 Nov	1-7 Nov	
	Cold prone region	Greater Rangpur and Rajshahi	1-15 Dec	20 Nov-7 Dec	
	Submerge area	Greater Cumilla, Khulna, Jashore (Vhobodaho)	7-21 Nov	1-10 Nov	
	Salinity area	Coastal area	1-15 Nov	-	
	BROUS (Late Boro)	Greater Rangpur	15-28 Feb	-	
Aus	Broadcast	Aus growing region	30 Mar-15 Apr	-	-
	Transplant	Aus growing region	1-30 Apr	-	15-20

c. **Over-aged seedling.** Over-aged seedlings of rice reduce a significant amount of yield which varies over the season. Yield reduces significantly because of per day increase in seedling age. Transplanting optimum seedling age should be practice gradually in all regions depending on rice variety, season, and ecosystem.

d. **Imbalanced use of fertilizers and other inputs.** Imbalanced use of N, P, K, S, Zn fertilizer affect the growth and development of rice and induces disease and insect development. Especially farmers fail to apply urea fertilizer timely with accurate dose. As a result, reduced spikelet number per unit area and consequently reduce grain yield. By adopting balanced fertilizer and applying urea timely and accurately grain yield will be increased significantly.

e. **Weed management.** Failure to control weeds during the critical competition period decrease a significant amount of grain yield. Commonly recommanded weed management options are herbicide fb 1HW, 2HW/3HW and mechanical weeding fb 1HW. Weed management by any means within critical period is crucial for effective weed management in rice. Because it has been estimated that rice yield decreases by 0.75 – 1.00 kg for every 1 kg of weed biomass produced (IRRI,2003).

Table 5. Season wise and ecosystem-based seeding, transplanting and seedling age of rice in Aman season.

Agricultural region	Characteristic of variety	Seeding time	Transplanting time	Seedling age (day)	Comment
Greater Rangpur and Bagura region	Short duration	5th Jul- 5th Aug	25 Jul- 25 Aug	15-20	If seedling age > 20 days, reduce tillering and grain yield. Transplanting before 25 Jul- 25 Aug attack by rat and birds.
All over the country	Medium and long duration photosensitive variety	15 Jun- 15 Jul	15 Jul- 15 Aug	25-30	Certain yield reduce after each day late.
Flood prone and lowland	Late photosensitive variety	10 Jun- 5 Aug	20 Jul- 15 Sep	35-40	Late and long duration photosensitive variety.
Salinity tolerant variety	Coastal area	20 Jun- 25 Jul	25 Jul- 30 Aug	30-35	BRRI dhan40, 41,54 varieties could be planted up to 15 Sep.
All scented (Aromatic) and local varieties	Greater Dinajpur, Rajshahi, Naogoan, Jashore and others	5 Jul- 20 Jul	15 Aug- 1 Sep	35-40	All local and scanted varieties of Aman season.

f. **Spacing and other agronomic management.** Optimum plant population per unit area is a prerequisite for obtaining a higher yield of rice. Farmers failure to maintain proper spacing, caused a reduction of yield. On the other hand poor land preparation and higher transplanting depth which are also the causes for yield reduction in the farmers' field. During seedling uprooting, if the soil is dry roots of the seedling may injured, and decreased seedling quality and delayed transplanting shock, and may reduce grain yield. Maintaining proper spacing and good land preparation with optimum transplanting depth (2-3 cm) could add extra yield. Fertilizer largely contributes to rice yield in all the ecosystems followed by weed control. Moreover, rice yield decline due to over-mining of soil nutrients, organic matter depletion, floods and droughts, and the use of poor-quality seed.

Fundamentals of yield loss and management

Narrowing the yield gap

Yield/efficiency gap was defined as the difference between achieved yield/efficiency and potential yield/efficiency (Van Ittersum *et al.* 2013). The achieved yield can be measured directly, while the potential yield of a certain region can be simulated by a model. A proportion of 80% of the potential yield should be considered as the attainable yield (Cassman *et al.* 2003). Resource use efficiency (e.g., nitrogen, water and solar radiation) was defined as the amount of output achieved per unit input. Rong *et al.*, (2021) comprehensively review the currently available studies on yield and efficiency gaps for the world's major food crops in recent years. Based on more than 110 published papers, data from FAO and the Global Yield Gap and Water Productivity Atlas, Rong *et al.*,(2021) summarize the concepts, quantitative methods for gap analysis, yield limiting factors, and resource utilization efficiency of wheat, maize and rice (Bin and Ying, 2021).

In Bangladesh yield can be minimized following the model with different site specific and season wise approprite agronomic management and through properly addressing the stress prone area and promoting the integrated management plan. Rice growth stage based management practice and some necessary steps should be followed properly.

Considering figure 2, the following points to be considered to curtail the rice yield gap

- Timely seeding/ transplanting with optimum seedling age and spacing.
- Balanced fertilizer application (especially urea in time) and weeding in a critical period.
- Selection of shorter duration rice varieties with high yield potential to fit into the farmer's cropping pattern.
- To sustain soil productivity a programme regarding integrated use of organic and inorganic fertilizers should be undertaken.
- Strengthen the present linkage between research and extension to accelerate the dissemination of site-specific agronomic management among the farmers.
- Increase the yield by improving soil health, nutrient use efficiency, using efficient varieties.
- A synergy between agronomic technologies with soil and water, extension activities to bridge the yield and information gaps (Field days, adoption), the policy of governance, etc is needed.

Site-specific and season wise agronomic management

Smart technology such as location-specific variety, profitable cropping sequences, innovative cultural management, and appropriate agronomic management with smart dissemination using multiple means would maximize rice yield and minimize production barriers of rice. It is observed from different experimental results that rice yield could be increased by 0.74 t ha^{-1} by adopting proper agronomic management (Bhuiyan *et al.*, 2017). Site-specific nutrient management improved productivity and profitability in rainfed lowlands of the Philippines and get 6% more yield and reduce nitrogen use in the farmers' field (Banayo *et al.*,2018). Applying alternative fertilization practices like slow-release nitrogen fertilizer, organic fertilizer, straw return, green manure, instead of conventional fertilizers might improve rice yield and nutrient use efficiency in rice cropping systems in China. Furthermore, the recovery efficiency (REN), agronomic efficiency (AEN), and the partial factor productivity of nitrogen (PFPN) were increased by 6.0–34.8%, 10.2–29.5%, and 4.7–6.9%, respectively under the alternative fertilization options relative to conventional fertilization (Ding *et al.*, 2018). Fertilizer, seed, and pesticide use can be reduced in intensive lowland irrigated rice by following best management practices without yield penalty. In Thailand, it is found that the improved best management practice reduces cost by 26% and increases the profit of rice production (Stuart *et al.*, 2018). The adoption of these practices can lead to a more economically, environmentally, and socially acceptable rice production situation in Bangladesh.

Integrative and optimized crop management techniques, i.e., optimized density, optimizing N application and applying N at later growth stage, alternate wetting and moderate soil drying, applying rapeseed cake fertilizer, applying organic manure could achieve the dual goal of increasing grain yield and resource use efficiency through improving agronomic and physiological performances, especially increases in sink size and shoot and root growth, leading to higher grain yield and NUE, (Depeng Wan *et al.*, 2017; Zhang *et al.*, 2018).

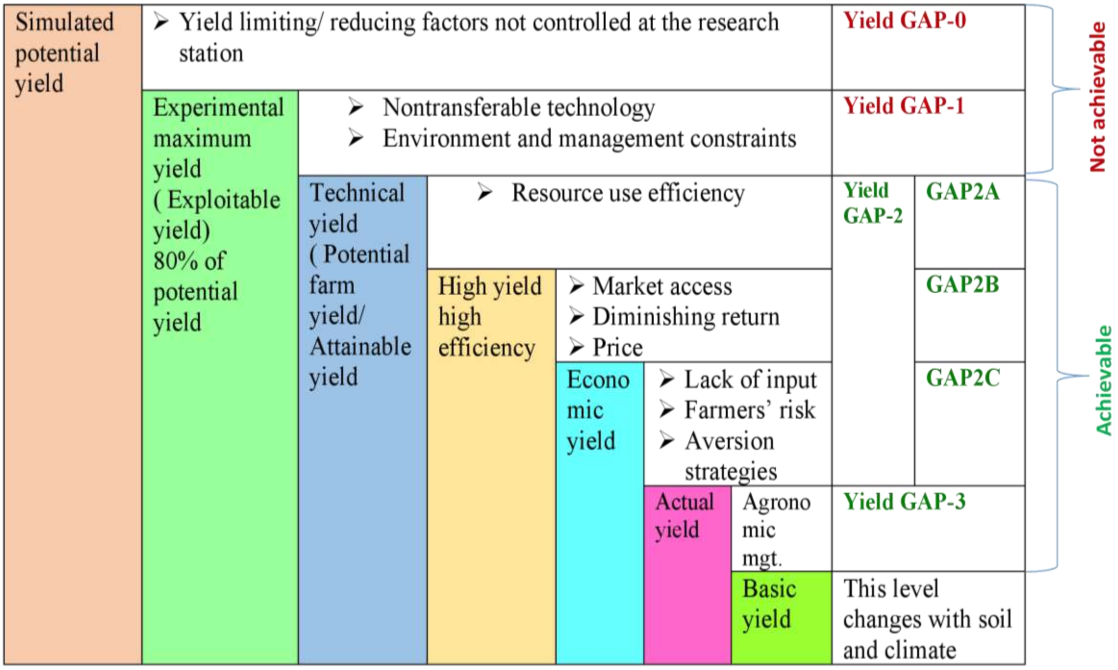


Fig. 2. Yield gaps and their main constraints. Yield Gap-0 cannot be reduced; Yield Gap-1 is the gap between the yield produced at experimental station level and farmland level; Yield Gap-2 is the gap caused by different management practices at the farmland level; Yield Gap-3 is the gap between farmland and fallowland, and caused by water, fertilizer, and other management measures.

Source: Modified from Ong Liang-bing ***et al.,2021***

Yield reduction could be triggered by per day increased seedling age in a different season. If grwers planted older seedlings instead of recommended seedling age a significant grain yield reduction occurred. Yield reduction had been calculated per day based on increased seedling age (kg ha^{-1}) in Boro season 24-40, cooler regions of Boro 2-125, T. Aus 1-37, T. Aman 2-77 and late T. Aman 1-71 (Ahmed *et al.*, 2006). So, appropriate variety and location-specific crop management systems should be formulated for yield maximization in rice to reduce the yield gap in farmers' fields. A number of approaches can be undertaken:

- Adopting location-specific crop production techniques.
- Manipulating sowing and planting times and use of optimum seedling age according to location-specific rice ecosystem and variety.
- Appropriate weed management technology in proper time.
- Suitable variety selection according to rice ecosystem and cropping pattern and for improving cropping intensity.
- Judicious and balance application of organic and inorganic fertilizer application.

Approaches for increasing and sustaining site-specific rice production and productivity of stress-prone area

Flash Flood, drought, and salinity are the main stress environments in Bangladesh where rice frequently suffers from considerable shock to maintain its full yield potential. The nature and extent of these environments vary with season, topography, and location.

Drought management strategy

- BRRI scientists identified drought risks of varying intensities for medium duration (140 days) varieties.
- Transplanting between 5 July to 25 July might have less risk of encountering drought. Short duration (115-120 day) rice varieties like BRRI dhan66, BRRI dhan71, BRRI dhan75, BRRI dhan33, BRRI dhan39, Binadhan-7 could avoid the terminal drought if they are transplanted by 15 July in the drought-prone area.
- Some of the varieties like BRRI dhan56, BRRI dhan57, BRRI dhan62 can be grown within 100-110 days in order to escape drought.
- After harvesting these crops by mid-November, farmers can go for wheat and then mungbean cultivation.Therefore T.Aman (short duration)-Wheat-Mungbean is an adaptable cropping pattern in a drought-prone area.
- The potentiality of T. Aman rice would be increased up to 30% provided the crop is satisfied with supplemental irrigation.This could be done by BRRI designated rainwater harvesting reservoir having the size of 4-5% of the command area.

Sustainable increase of rice production in Aus ecosystem require:

- Assurance of partial or supplemental irrigation facilities in Aus season to confirm the establishment of direct dry seeded Aus.
- Weed is a serious problem for direct-seeded Aus rice. So it needs attention for successful and economic weed management in direct-seeded rice.
- Location-specific varieties along with production technologies will be the crucial factors for attaining the goal.
- For timely establishment and post-harvest operations, farm mechanization needs to be emphasized.
- Some fallow areas in the South and North-eastern region should be brought under cultivation like Barishal and Sylhet region.

Sustainable increase of rice production in haor areas require:

- Some of the agronomic practices and varietal intervention might be helpful to reduce the growth duration of boro rice crop and increase grain yield.
- Cold-tolerant and short-duration rice varieties (120-135 days) need to be developed for the farmers in Haor regions which will be at least 15 days earlier than the existing common practice.
- Rice seedlings grown from an imposed high temperature (grown under polyethene cover) might have some more accumulated temperature at the seedling stage to reduce the growth duration to some extent.
- Direct seeding is another way to reduce the growth duration by about 2weeks.
- Early seeding/transplanting can avoid flash floods in hour areas.

Recommended Strategies and way forward for sustainable increase of rice production in haor areas are given in figure 3.

Sustainable increase of rice production in coastal areas

Following agronomic practices might be helpful to reduce salinity:

- Winter is relatively short in the coastal region. So the establishment of Boro a month earlier might help to avoid higher salinity during April-May.
- Straw mulching conserves water and reduces the capillary rise of saline water

and prevents forming the saline crust. Soil flashing (washing soil with fresh water) four times is good for reducing soil salinity during Boro season, one time flashing during the reproduction phase is quite useful for the crop. Integrated fertilizer management is quite beneficial for a growing crop in a saline-prone area. Dibbling rice seeds in Aus season help to avoid direct contact of seedling with saline crust at the upper layer of the soil.

- Cultivation of Dhaincha as a crop in T. Aman-Fallow cropping pattern to reduce capillary movement of salty water through evaporation.
- Transplanting 45 – day- old seedlings with 3-4 seedlings $hill^{-1}$ is recommended because the relatively aged seedlings attain tolerance at the late seedling stage.
- Nitrogen management with USG is another option to obtain a higher yield in T. Aman season in saline areas.

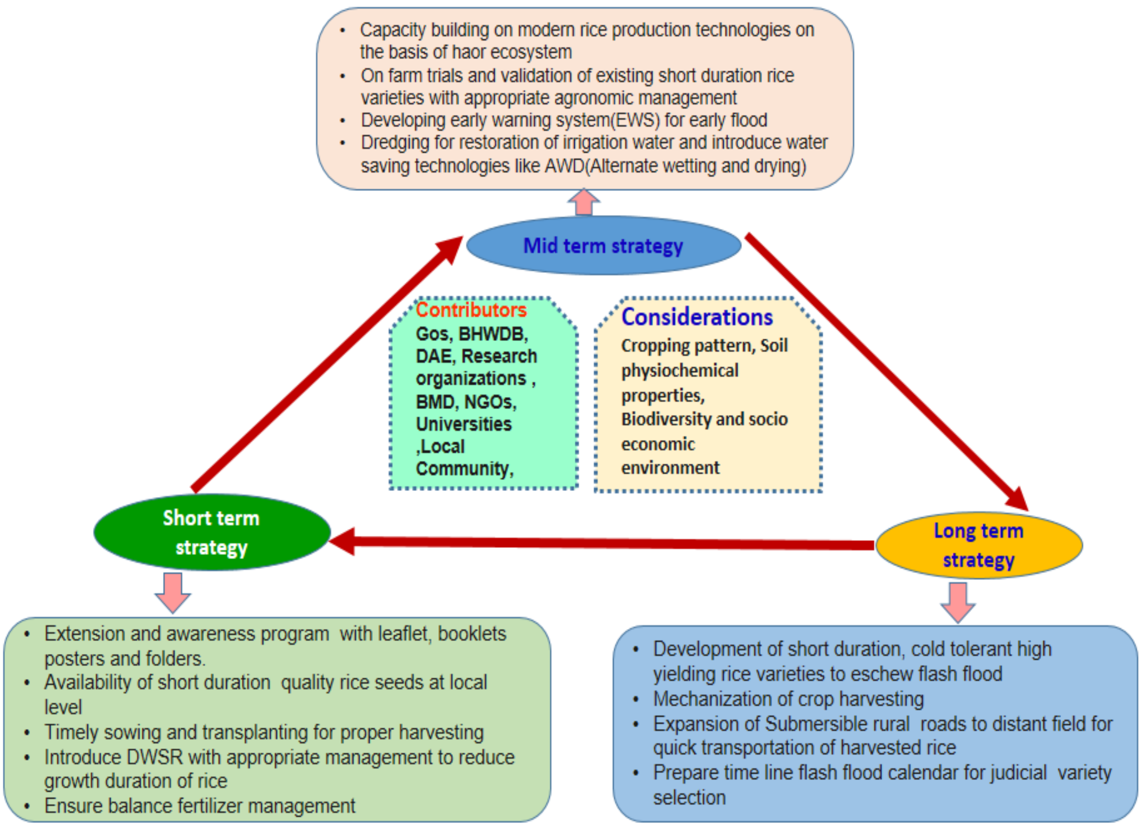


Fig. 3. Framework for sustainable increase of rice production in haor areas
Source: Modified from Kamruzzaman and Rajib (2018)

Fertilizer management strategy for sustainable rice production

The role of chemical fertilizer in rice yields is currently 59-69% only, but its use with organic nutrient sources can help in improving rice grain yield. The use of organic and inorganic nutrients is responsible for obtaining 0.78-117% higher yield compared to chemical fertilizer alone (Nahar *et al.*, 2018). Application of biofertilizer along with 50% reduction of N and P produced 32% higher rice yield over chemical fertilizer (Nahar *et al.*, 2018). Green manuring with sesbania improves soil carbon status and increases yield by 9-11% over chemical fertilizer.

Moreover, use of approaches for sustainable nutrient management (Fig.4) including appropriate soil testing technique, fertilizer sources (organic, inorganic, biofertilziers and nanofertilizers) and application method in right combination using site specific nutrient management will reduce the fertilizer losses with high NUE and economic yield. So sustainable and ecosystem-friendly rice production depends on the combined use of organic and inorganic fertilizer in the future.

Promotion of integrated crop management plan (ICMP)

Integrated crop management (ICM) is a approach farming that aims to balance production with economic and environmental considerations by means of a combination of measures including crop rotation, cultivations, appropriate crop varieties, and careful use of inputs. It combines the best of traditional methods with appropriate modern technology, balancing the economic production of crops with positive environmental management.

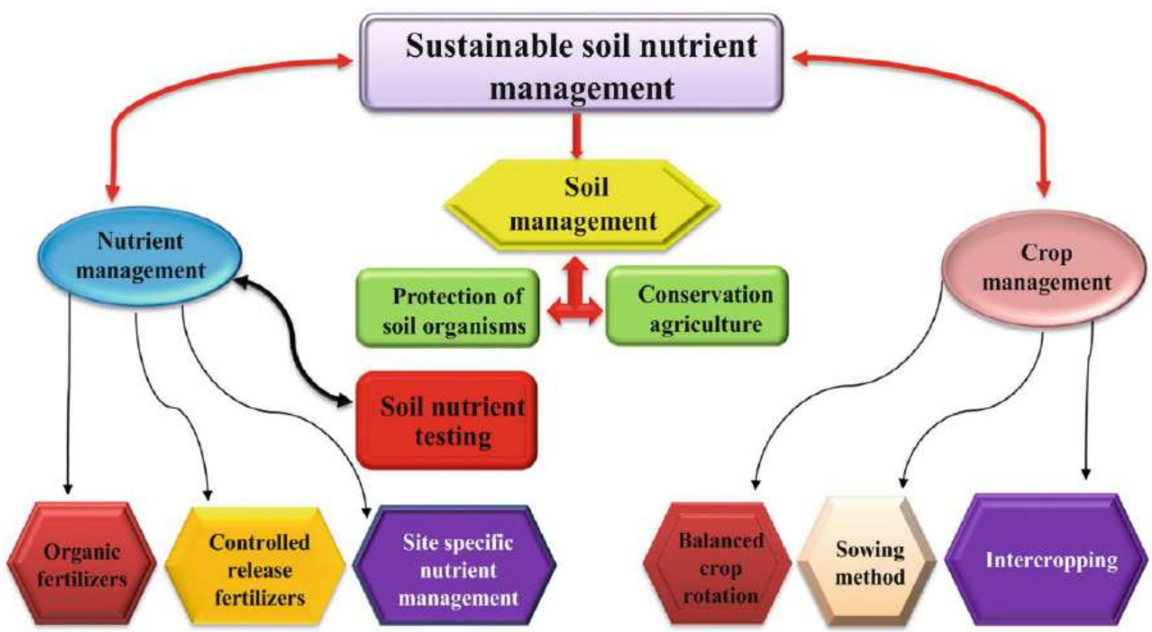


Fig. 4. Approaches for sustainable nutrient management

Source: Adopted from Rehman *et al.*, 2019

Basic components of ICM are crop management, nutrient management, pest management and financial management. Each of these components is associated with agricultural Best Management Practices (BMP). Each BMP overlaps between the broader components of ICM. In the end, ICM and subsequent improved use of on-farm resources cause a reduced dependency on outside inputs of fertilizers, pesticides, and herbicides through the integration of farm management components and best management practices.

A maximum rice grain yield of 9.40 and 10.53 t ha^{-1} was achieved under ICM in China (Depeng *et al.*, 2017), indicating the potential to further increase the grain yield of rice following a holistic and integrated agronomic approach. Optimum crop management especially nutrient management has proven to be highly effective in improving rice grain yield. Other management practices such as planting methods and plant density, quality of seeds and seedlings, and irrigation regime can also affect grain yield to some extent. Depeng *et al.*, 2017,stated that testing a single component of management practices independently may not capture the impact of a holistic package would have on enhancing rice grain yield. He stated that closing the yield gap is becoming increasingly difficult to achieve by using a component technology in isolation.

Suitable improved varieties and improved cultural practices including integrated pest management and integrated plant nutrition management are the main components of ICMP. A number of innovative technologies identified by CREMNET (Crop and Resource Management Network), IRRI, may provide effective tools to partly narrow yield gaps in rice production for small farmers in developing countries. CREMNET works on the chlorophyll meter technique, leaf color chart for field-specific N management, urea tablet deep placement, direct wet-seeding method, etc. (IRRI, 1997) and is appropriate for inclusion in integrated crop management packages to narrow gaps in rice production in developing countries.

General steps for yield loss management

To grow rice and get higher yield farmers should follow different steps. If farmers plan and follow the mentioned below steps, rice productivity will be increased (Table 6).

Rice growth stage-wise agronomic management

Each growth stages of rice requires some specific management practices. We have to follow the specific agronomic management to get higher yield and sustainable productivity (Table 7).

To achieve the target by 2020-2050, we have to settle a masterplan and accordingly we have to implement all those protocols step by step.

Location, variety and site specific smart agronomic management: Action Plan for each SABM (Stagewise Agronomic Broad Management)

Table 7 presents rice stagewise agronomic management practices was. However, Table 8 indicates how this action plan will be implemented in a synchronized way by adopting different broad agronomic management. In this process in each growth stage and phase should have to perform some specific actions like framework development, screening, calibration, and technology validation. Therefore a mature smart agronomic management (Fig 5.) will be coming out. Continuous observation is needed on how these technologies are being performed. It will follow by massive demonstrations in the farmer's field and training for different stakeholders. It was explained how this action plan will work for a specific rice stage.

Table 6. Steps to follow to obtain higher yield.

Step	Activity/Management
i. Using a crop calendar	A good crop calendar help the selection of a good variety in a cropping system and helps to organize other farm activities in cropping sequences.
ii. Choosing the best variety	It is required to select a variety according to rice ecosystem, cropping system and with high yielding ability.
iii. Using high-quality seed	It is needed to use quality seed, because it reduces the required seeding rate and produces strong, healthy seedlings, resulting in a more uniform crop with higher yields.
iv. Prepare and level the fields well	A well-prepared and leveled field gives a uniform, healthy crop that can compete with weeds, uses less water, and give higher yields.
v. Plant on time	The best time to plant (Transplant/direct seeding) depends on the locality, rice ecosystem, soil type, and topography. Transplanting/seeding on time is very important because late/early planting reduces rice yield and interrupt cropping systems.
vi. Monitoring and surveillance and following weather-based forecasting	Time to time monitoring and surveillance will help the rice plant to remain free from nutrient disorder, weeds, insect, and disease and keep free from any kind of natural disaster.
vii. Timely weeding	Weeds compete directly with the rice plants and reduce rice yield. Each one kg dry matter of weeds is equivalent to one kg grain loss. Weeds cause most yield loss within the first 20–50 days after crop establishment. Weeding after panicle initiation may also be important to prevent weeds shedding seeds in future crops.
viii. Fertilize timely and effectively	The amount and type of fertilizer applied are determined on the assumption that one ton of grain will remove 15 kg nitrogen (N), 2–3 kg phosphorus (P), and 15–20 kg potassium (K). These base rates need to be modified according to the soil type, the season, the crop condition, prevailing weather conditions, and efficiency of the application.
ix. Use water efficiently	Manage water in rice field efficiently. Because Good water control increases rice yields and grain quality as well as improving the efficiency of other inputs such as fertilizer, herbicide, and pesticides.
x. Control pests and diseases effectively	If there are pest or disease incidences in the rice field, it is important to diagnose the problem accurately. For help with the diagnosis, seek advice from a professional. If decided to apply chemicals, carefully read and follow the instruction of labels.
xi. Harvest on time	Harvesting the crop on time is very important to maximize yields and grain quality. Harvest when grain moisture is between 20–22%; 80–85% of the grains are straw-colored; grains in the lower part of the panicle are hard, not soft; and grains are firm but not easily broken when squeezed between the teeth.
xii. Store safely	Rice is best stored as paddy because the husk provides some protection against insects and helps prevent grain quality deterioration. Stored rice maintain < 14% moisture for grain and 12% for seed using bags/ drams or in following other methods.
xiii. Mill efficiently	Milling rice paddy removes the husk and bran layer to produce white rice. Rice is best milled at 13–14% moisture content. milling properly to get optimum head rice.
xiv. Understand the market	The value of milled rice in the market is determined by variety and a number of physical and chemical characteristics of the variety and the consumers, which will vary within and between countries.

Table 7. Stagewise agronomic management consideration for obtain higher yield.

Growth phase	Growth stage	Probable range	Consideration for agronomic management
Vegetative phase	1. Germination	3-5 days	• Proper soaking of seeds • Above 40 ^{0}C no germination • Below 10 ^{0}C no germination
	2. Seedling (seedling to transplanting days depends on season- Aus, Aman and Boro)	15-45 days Note: Boro season >150 days long duration and <150 days short duration. Aman season <120 days; short duration, 120-135 medium duration, and >135 days long duration. Aus season usually short duration (100-120 days)	• Care of seedling in the seedbed: Sufficient moisture, should follow seedbed protection from the cold. Like hold 4-5 cm water in seedbed and use transparent polythene cover from 10 am to till evening • Apply organic matter or fertilizer urea (5-7 g m^{-2}) if needed. • Avoid stress during seedling pulling • Minimum transplanting shock • Maintain 2-3 cm transplanting depth • Transplant 2-3 seedling hill^{-1} and maintain 20x20 cm spacing • Follow line and logo method with north-south direction for better aeration and reduce pest attack. • Maintain seedling age according to season and growth duration • Maintain transplanting time • Apply basal fertilizer
	3. Tillering	35-60 days	• First top-dress (1/3rd) urea application • Weed management (herbicide/ hand weeding/ mechanical weeding) • Disease and insect management • Water management
	a) Active tillering	30-55 days	• Second top-dress (1/3rd) urea application
	b) Maximum tillering	3-5 days	• Just before panicle primordia must apply the last top-dress of urea (1/3rd) which is called panicle fertilizer. Because at this stage panicle determined the spikelet number and the absorbed nitrogen is efficiently used to increase spikelet number, accumulated photosynthates to leaf sheath and culm and, hence, increase panicle size and grain yield.
Reproductive phase	1. Panicle primordia	0 days	• Split application of K
	2. Primary branch primordia	3 days	• Keep water in the field • Manage drought
	3. Secondary branch primordial	3 days	
	4. Stamen and pistil primordial	4 days	
	5. Pollen mother cells	3 days	
	6. Meiotic division	5 days	
	7. Mature pollen	6 days	
	8. Ripe stage of pollen	2 days	
	9. Completed spikelets	2 days	
	10. Flowering	2 days	
Ripening phase	1. Milk	7-9 days	• Mange sucking type insect-like; rice bug
	2. Soft dough	5-7 days	
	3. Hard dough	5-7 days	• Drain water
	4. Maturity	8-12 days	

Source: Yoshida, 1981; BRRI (2019)

A framework was formulated by using different tools and techniques through literature, review, and experience (Fig. 6). This is the output of SAM-i. The screening will be done from the framework by experience, brainstorming, and group discussion. This is SAM-ii. It will calibrate and validate a technology through laboratory testing, nethouse, and field evaluation of SAM-ii. It may need a multilocation trial especially to the location where the SAM will be applied.After fulfillment of all targets, it may not be work. Again we have to do the same process (Fig. 6). Mature technology must go to the farmers' field in the respective domain for demonstration and training (Fig. 6).

To fulfill SDGs goals and beyond Table 9 indicates how these action plans will work after 2030 to 2050. The action will be followed thereafter and when necessary research and development studies will be going on.Table 9a, 9b, and 9c indicate rice stagewise research and management for primary level, intermediate level, and maturation level which will be followed up during the next period of 2030 to 2050. In addition, in each level of the research and development phase, have some specific action plans (Tables 9a, 9b and 9c). All these smart agronomic management practices will depend on rice growth phases and stages, and it will be implemented by variety, season, location, and ecosystem-based.

Table 8. Location, variety and site-specific smart agronomic management: action plan for each SABM (Stagewise Agronomic Broad Management).

Programme	Phase	Stage	Action
Research and Development (Broad Agronomic Management) • Ensure desired germination (BM1) • Location, variety and site-specific sowing and transplanting time (BM2) • Seedling age at transplanting (BM3) • Top dressing fertilizer (BM4) (climate specific) • Top dressing fertilizer (BM4) (climate specific) • Water management (BM5) • Harvesting (BM6)	Vegetative	VP1-VP4	o Framework development o Screening o Calibration o Validation o Mature SAM (Smart Agronomic Management)
	Reproductive	RP1	o Framework development o Screening o Calibration o Validation o Mature SAM
		RP2-RP10	o Validation o Mature SAM
	Ripening	RIP1-RIP2	o Validation o Mature SAM
		RIP-4	Mature SAM
	Follow up	CO	o Continuous observations to keep on notice if changes happening on the smart agronomic management package. If the technologies work well, it will be continue, if not works well, SAM will be reviewed. If review not possible either hold the SAM and start from screening to validation
Dissemination	Phase-1	Training	o Training (DAE officers and lead farmers)
	Phase-2	Demo	o Demonstration (Different locations of recommended domain)

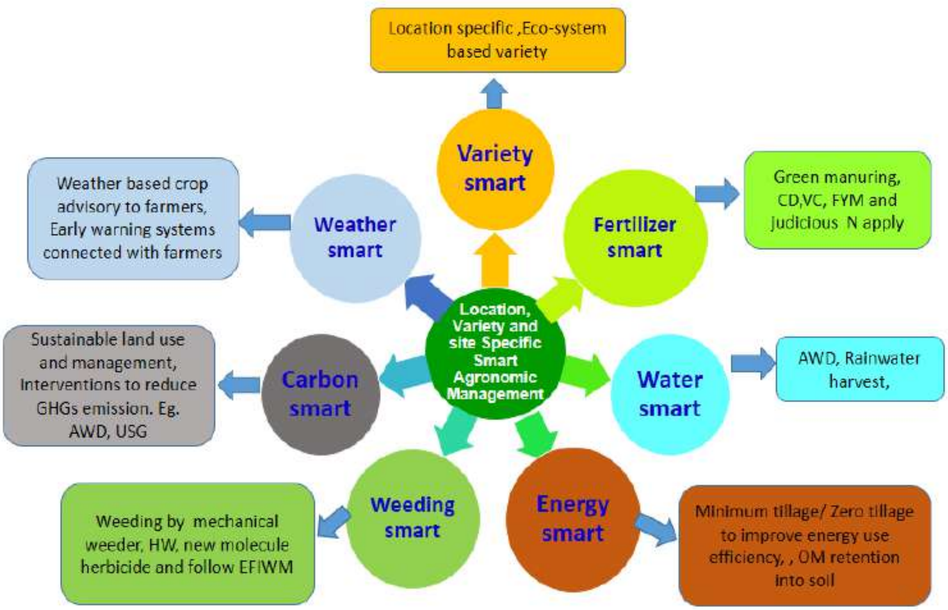


Fig. 5. Smart agronomic management.

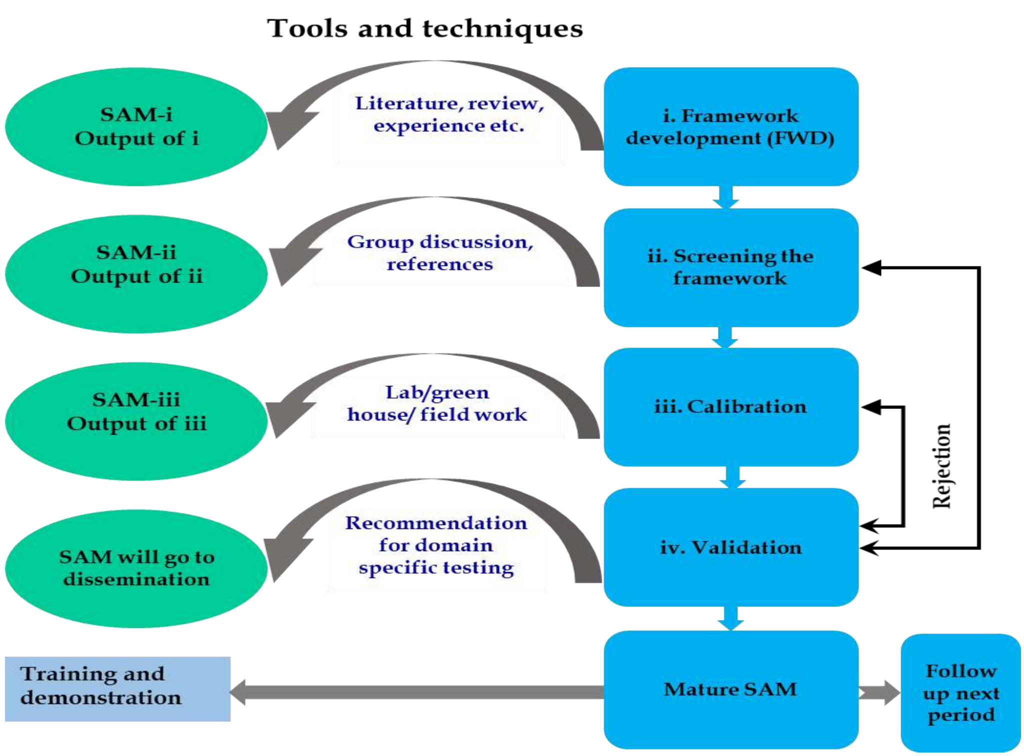


Fig. 6. Flow diagram for implementing action plan of each SABM (Stagewise Agronomic Broad Management).

Table 9. Variety and location-wise smart agronomic management from the period 2021-2030, 2031-2040 and 2041-2050.

a) Period 2021-2030

Rice growth phase and stage	Variety and location wise smart agronomic management								
	Period: 2021-2030								
	Research and development phase							Dissemination phase	
	Primary		Intermediate		Maturation		Follow up	Step-1	Step-2
	FWD	Scree-ning	Calibr-ation	Valid-ation	Cali-Valid	Mature SAM	CO	Train	Demo
VP1									
VP2									
VP3									
VP4									
RP1									
RP2-10									
RIP1-2									
RIP-4									

b) Period 2031-2040: Follow up SAM

Rice growth phase and stage	Variety and location wise smart agronomic management								
	Period: 2031-2040								
	Research and development phase							Dissemination phase	
	Primary		Intermediate		Maturation		Follow up	Step-1	Step-2
	FWD	Scree-ning	Calibr-ation	Valid-ation	Cali-Valid	Mature SAM	CO	Train	Demo
VP1									
VP2									
VP3									
VP4									
RP1									
RP2-10									
RIP 1-2									
RIP-4									

c) Period 2041-2050: Follow up of SAM

Rice growth phase and stage	Variety and location wise smart agronomic management								
	Period: 2041-2050								
	Research and development phase							Dissemination phase	
	Primary		Intermediate		Maturation		Follow up	Step-1	Step-2
	FWD	Screening	Calibration	Validatio n	Cali-Valid	Mature SAM	CO	Train	Demo
VP1									
VP2									
VP3									
VP4									
RP1									
RP2-10									
RIP 1-2									
RIP-4									

CONCLUSION

The productivity of rice varies not only in a different region but also within the same region depending upon different rice ecologies and production systems used. The intervention of modern varieties coupled with improved agronomic practices can result in reduction of the yield gap. Bridging the yield gap would not be easy given the agro-ecological and socio-economic diversity prevailing in the country. Research emphasis should be given on improving nutrient use efficiencies, optimum sowing and transplanting schedule with seedling age, and with special emphasis on site-specific nutrient management in rice and rice-based cropping and farming systems. Innovative approaches involving nano-technologies could be considered for efficient use of fertilizers and pesticides. It is essential, therefore, to promote closer collaboration between research, extension, local authorities, non-governmental organizations (NGOs), and private sectors in order to identify specific constraints to high yield and adopt appropriate technologies and solutions, and take concerted actions into consideration to bridge yield gaps of rice, through participatory approaches.

RECOMMENDATIONS

- The close collaboration and teamwork between farmers, researchers, extension, and commercial enterprise and industry needs to continue.
- Emphasis to be taken on the production of new crop varieties that offer higher yields but use less water, fertilizer, or other inputs and are more resistant to drought, salinity, heat, submergence, and pests and diseases.
- Need a country-wide massive programme to increase soil organic matter by green manuring, farmyard manure, or any other organic amendments.

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AUTHORS' CONTRIBUTION

MKAB generated idea; AKMSI, MARS, MAAM, MUS and MSK coordinated the research; MKAB developed methodology, gathered data, carried out analysis and synthesis; MKAB and MUS provided scientific insights; MKAB did the writings for all versions of the manuscript; MARS, MAAM, MUS and MSK performed critical review and editing; All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

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Acronyms and Abbreviations

BRRI= Bangladesh Rice Research Institute
BINA= Bangladesh Institute of Nuclear Agriculture
T. Aman= Transplanted Aman rice
IRRI= International Rice Research Institute
SAM= Smart Agronomic Management
SABM= Stagewise Agronomic Broad Management
DAE = Department of Agricultural Extension
GO = Government organization
ICM = Integrated crop management
IPM = Integrated pest management
NGO = Non-government organization
SDG = Sustainable development goal
BMP= Best management practices
ICMA= Integrated crop management plan
ICM= Integrated crop management
DAS= Days after sowing
DAT= Days after transplanting
DAP= Days after planting
CREMNET =Crop and Resource Management Network
DAE= Department of Agriculture Extension
SM= Smart management
FWD = Frame work development
Mtg-FWK = Management framework
Cali-Valid = Calibration and validation
Sm-Mtg = Smart management
CO = Continuous obervation
Train = Training
Demo = Demonstration

Rice growth phases and stages related Acronyms and Abbreviations

Growth phase	Growth stage	Symbolic name	Abbreviation
Vegetative phase	1. Germination	Vegetative phase 1	VP1
	2. Seedling	Vegetative phase2	VP2
	3a. Active Tillering	Vegetative phase 3	VP3
	3b. Maximum tillering	Vegetative phase 4	VP4
Reproductive phase	1. Panicle primodia	Reproductive phase1	RP1
	2. Primary branch primodia	Reproductive phase2	RP2
	3. Secondary branch primordia	Reproductive phase3	RP3
	4. Stamen and pistil primordia	Reproductive phase4	RP4
	5. Pollen mother cells	Reproductive phase5	RP5
	6. Meiotic division	Reproductive phase6	RP6
	7. Mature pollen	Reproductive phase7	RP7
	8. Ripe stage of pollen	Reproductive phase8	RP8
	9. Completed spikelets	Reproductive phase9	RP9
	10. Flowering	Reproductive phase10	RP10
Ripening phase	1. Milk stage	Ripening phase1	Rip1
	2. Soft dough	Ripening phase2	Rip2
	3. Hard dough	Ripening phase3	Rip3
	4. Maturity stage	Ripening phase4	Rip4