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A Way Forward to Combat Insect Pest in Rice

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ABSTRACT

The damage caused by insect pest is the continual factor for the reduction of rice production. To date, 232 rice insect pest species are identified in Bangladesh and more than 100 species of insects are considered pests in rice production systems globally, but only about 20 - 33 species can cause significant economic loss. The major goal of this study is to explore all the possible ways of developed and proposed technologies for rice insect pests management and minimize economic losses. Insect pests cause 20% average yield loss in Asia where more than 90% of the world's rice is produced. In Bangladesh, outbreak of several insects such as rice hispa, leafroller, gallmidge, stem borers and brown planthopper (BPH) occurs as severe forms. Based on previous reports, yield loss can reach upto 62% in an outbreak situation due to hispa infestation. However, BPH can cause 44% yield loss in severe infestested field. To overcome the outbreaks in odd years and to keep the loss upto 5%, it is necessary to take some preventive measures such as planting of resistant or tolerant variety, stop insecticide spraying at early establishment of rice, establish early warning and forecasting system, avoid cultivation of susceptible variety and following crop rotation. Subsequent quick management options such as insecticidal treatment for specific insect pest should also be broadcasted through variety of information systems. Advanced genomic tool can be used to develop genetically modified insect and plants for sustainable pest management. In addition, to stipulate farmers not use insecticides at early crop stgae and minimize general annualized loss, some interventions including training rice farmers, regular field monitoring, digitalization in correct insect pests identification and their management (example; BRRI rice doctor mobile app), and demonstration in farmers field. Each technology itself solely or combination of two or more or all the packages can combat the insect pests, save natural enemies, harvest expected yield and contribute to safe food production in Bangladesh.

Key words: Insect pests, rice, management, safe food, increase productivity

INTRODUCTION

Insect pest is a major constraint to rice production. Rice plants are vulnerable to insect feeding at the time of sowing till harvesting. Both the mature and immature stages of insects can injure rice plants by chewing leaf and root tissues, boring and tunneling into stems, or sucking fluid sap from stems and grains. However, insect pest attacks frequently occur with varying intensities and frequencies possibly induced by the changes in climate and cropping systems in modern rice cultivation. Two hundred sixty-seven insect pest species, 185 parasitoids, and 192 predators are known to occur in Bangladesh rice ecosystems (Islam and Catling, 2012; Islam *et al*., 2003; Ali *et al*., 2017). However, 20 - 33 species are considered significant pests capable of causing yield losses if they infest plants in sufficiently large numbers (Table 1). The insect attacking rice can be divided into major and minor pests. The major pest is those which frequently cause very distinct economic damage and minor pests are those insects which are often found but cause less serious damage (Halteren, 1979). To control insect pests, insecticides are applied 2-4 times each season in rice fields (Haque, 2014), resulting in 6-12 pesticide applications per year. Agricultural production practices used 39,464 tons of pesticides in 2014 (BPCA, 2015), with over 80% used in rice fields to combat pests and diseases (BBS, 2015). Thus insect pest sometimes causes the barrier to sufficient food production in Bangladesh. Kabir *et al*. (2015) outline different smart technology such as location-specific variety, profitable cropping sequences, innovative cultural management, and mechanization coupled with smart dissemination approaches to overcome this barrier.

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Predators and parasitoids often attack these pests and control them naturally in the field. Over the last three decades, the introduction of high-yielding rice varieties to feed the fast-growing human population in developing countries, such as Bangladesh, has resulted in the use of large quantity of chemical insecticides. This heavy reliance on chemical insecticides reduces natural enemy populations in rice landscapes, promoting pest outbreaks (Heong *et al.*, 2015). Intensive rice production with the primary goal of achieving high yield is often characterized by the excessive application of fertilizers and pesticides.

It has led to many negative environmental effects, such as the reduction of biodiversity and natural biological control, high pesticide residues in rivers, drinking water, and agricultural products, rapid and high insecticide resistance in pests, secondary pest outbreaks, environmental pollution, and ecological imbalance. These severe negative effects will damage the ecosystem, lead to frequent pest outbreaks, and in turn require an increased pesticide dosage, which forms a vicious circle (Conway and Pretty, 1991). Excessive and irrational use of pesticides has become a major obstacle to sustainable agriculture in Bangladesh and is also threatening food safety and human health.

Recently, new principles, technologies, and strategies of pest management have been developed. One of the principle is 'green plant protection', which has been widely accepted (Lu *et al.*, 2012; Ye, 2013). Ecological control practice is another set of strategies introduced to reduce insecticide use, and one of the strategies is ecological engineering (Ali *et al.*, 2019; Gurr *et al.*, 2016). With the above background, this article undertook three specific objectives in relation to rice insect pests in Bangladesh: (i) scenario of their changing status, (ii) highlighting the scenarios of yield loss associated with the insect pests, and (iii) development and mapping the action plan for three decades on reducing yield loss from the insect pests.

METHODOLOGY

First, we explored the rice yield loss due to insect pests in Bangladesh. Several literatures were taken in mind and finally set up a national yield loss of rice production in Bangladesh (Tables 2 and 3). All data and several ideas were collected from secondary sources. A simple diagram has been proposed to make network between farmer's field problems and researchers through GIS. The idea for the model/diagram was adopted from different reports, has been modified by the authors. The baseline data for yield loss has set after a thoroughly discussion by a group of rice scientists worked in doubling rice productivity by 2030, on 11 November 2019. Except abnormal year (when pest outbreak occurs frequently), we assumed and fixed that the insect pest causes 1.0% national average yield loss of rice every year. However, the literature on rice yield losses due to insect pests in Bangladesh are different due to yield loss assessment methods. The reported findings were obtained from experimental plots comparing to control one where insect pest management practices were not allowed or a survey report obtained from a pest outbreak field. This is not happened in total production areas of the country in any year. Therefore, we can not calculate the total national loss based on this report. Typically, insect pests cause 18% yield loss to rice production in experimental plots when compared to the control plot (no actions were undertaken) in Bangladesh. Currently, control of these arthropod pests solely depends on chemical pesticides (Islam *et al.*, 2003). During 2011 and 2012, about 20–24 thousand tons formulated (as an active ingredient, a total of 1900-2400 tons) insecticide was used in Bangladesh (BCPA, 2013) with more than half of that amount applied against rice insect pests. Therefore, alternatives control approaches and forthcoming novel concepts were explored and described here. Based on this study, several recommendations were made for current and future studies.

RESULTS AND DISCUSSION

Status of rice insect pests in Bangladesh

Table 1 presents the pest order and their status to date. These insect pests cause losses in rice production. Insect pests attack all portions of the rice plant and all stages of plant growth. Feeding guilds consist of (1) root feeders, (2) stem borers, (3) leafhoppers and planthoppers, (4) defoliators, (5) grain suckers, and (6) ear cutting insects. Insects also attack rice grains in storage.

Table 1. List of major* rice insect pest and changes their status in Bangladesh from 1965 to 2019.

1965 (Alam 1965)	1977 (BRRI literature review)	2009 (Islam *et al*., 2009)	2020 (Based on outbreak observation)
Major pests[1]	Major pests	Major pests	Major pests
1. Rice ear-cutting caterpillar	1. Rice stem borers (YSB, DHB, PB)	1. Stem borers	1. Brown Planthopper
2. Rice swarming caterpillar	2. Green leafhoppers	2. Brown planthopper White backed Planthopper	2. Stem borers
3. Rice stem borers (YSB, DHB, PB)	3. Rice ear-cutting caterpillar	3. Rice hispa	3. Rice leaffolder
4. Rice hispa	4. Rice gall midge	4. Rice gall midge	4. Rats
5. Rice bug	5. Rice hispa	5. Rice bug	5. Green leafhopper
6. Green leafhoppers	6. Rice bug	6. Rice leaffolder	6. Rice hispa
7. Rice caseworm	7. Rice leaffolder	7. Green laefhoppers	7. Rice gall midge
8. Rice mealybug	8. Rice swarming caterpillar		8. Rice bug
9. Rice grasshoppers[2]	9. Rice caseworm		9. White backed planthopper
10. Field cricket	10. Rice mealy bug		
11. Rats	11. Rice whorl maggot		
Minor pests	Minor pests	Minor pests	Minor pests
1. Whitebacked planthopper	1. Rice grasshoppers[2,3]	1. Ear-cutting caterpillar	1. Whorl maggot
2. Rice grasshoppers[3]	2. Rice thrips	2. Swarming caterpillar	2. Ear-cutting caterpillar
3. Rice gall midge	3. Orange-headed leafhopper	3. Mealy bug	3. Rice thrips
4. Rice leaf roller (leaffolder)	4. Field cricket	4. Whorl maggot	4. Caseworm
5. Rice hairy caterpillar	5. Rice leaf beetle	5. Caseworm	5. Small brown planthopper
6. Rice leaf beetle[4]	6. Brown planthopper	6. Field cricket, Long-horned cricket	6. Rice grasshoppers[3]
7. Rice thrips	7. Rice hairy caterpillar	7. Rice thrips	7. Rice skipper
8. Rice skipper	8. Rice leaf butterfly		8. Rice mealybug
9. Rice leaf butterfly	9. Rice skipper		9. Long-horned cricket
			10. Field cricket
			11. Mole cricket

[1]Number associated with each pest represents the rank of pest status in the respective reported year; [2]*Hieroglypbus baniar*; [3]*Oxya* spp; [4]*Leptispa pygmaea*; YSB-yellow stem borer, DHB-dark-headed borer, PB-pink borer.*The major pests are those which frequently cause a very distinct economic damage and minor pests are those insects which are often found but cause less serious damage (Halteren, 1979).

At the last count in 2003, 644 arthropod species have been observed in Bangladesh: 267 phytophagous insects, 192 predators, and 185 parasitoids (Islam and Catling, 2012; Islam *et al*., 2003). However, we can see that there have been several assessments and that the pest status has shifted significantly over the last 60-70 years. Hazarika (1952) reported six rice pests: the yellow stem borer was the top of the list, followed by rice swarming caterpillar, rice hispa, rice bug, rice ear-cutting caterpillar, and the rice caseworm. Alam (1965) reported 20 significant pests of which 11 are considered as major pests. The major pests are those which frequently cause very distinct economic damage and minor pests are those insects which are often found but cause less serious damage (Halteren, 1979).

Fig. 1. Rice root feeder and its damaged symptom observed in rice field. A. Wingless adult (root aphid) feeding on root. B. Visible field damaged caused by root aphid; C. Uprooted rice plant with root feeding damage by white grub; D. Water weevil (adult) on rice plant; E. Rice black beetle (Scarabaeid beetle). Image taken from IRRI Knowledge bank.

Root feeders

Figure 1 shows the beetle and its damaged symptom. Examples of root feeders are scarabaeid beetles, and the rice water weevil, *Lissorhoptrusoryzophilus* (order Coleoptera). Black beetle feeds on the roots and severely reduces the root system. The adult water weevil feeds on the leaves and causes little damage while the larvae feed on the roots and severely reduce the root system.

Plants with reduced root systems grow poorly and have low yields. The scarabaeid beetles *Heteronychus lioderes* burrow into the base of the rice plant. Peak activity period is at night. They burrow underground and damage many plants, causing patches of dead plants in the fields. Beetles also damage irrigated crops in flooded fields. Beetles lay eggs a few days after emergence. About one month later grubs begin to cause damage. They feed on roots, rootlets, and root hairs. They also make damage plant by chewing the base of the stem just above the roots. Attacked plants can easily be pulled from the soil.

Stem borers

Figure 2 demonstrates the yellow stem borer and its damaged symptoms. Stem borers consist primarily of insects in the lepidopterous families, Noctuidae and Pyralidae. Three species of rice stem borers including yellow stem borer (*Scirpophaga incertulas*), dark-headed stem borer (*Chilo polychrysa*), pink stem borer (*Sesamia inferens*) are commonly found in Bangladesh. Among them, yellow stem borer is the most dominant species in Bangladesh.

The adult moths lay eggs on rice leaves and the larvae bore into the stem. Feeding in the stem during the vegetative growth stage of the plant (seedling to stem elongation) causes death of the central shoot ("deadheart"). Damaged shoots do not produce a panicle, and thus, produce no grain. Feeding of stem borers during the reproductive stage (panicle initiation to milk grain) causes a severing of the developing panicle at its base. As a result, the panicle is unfilled and whitish in color, rather than filled with grain and brownish in color. Such empty panicles are called "whiteheads".

Fig. 2. Yellow stem borer and its damaged symptoms observed in the field. A. Deadheart observed at the vegetative stage; B. Whitehead observed at the reproductive stage; C. Female adult moth; D. Male adult moth; Egg mass observed in rice leaf; F. Larvae of stem borer. Some photos taken from IRRI and BRRI rice knowledge bank.

Leafhoppers and planthoppers

In general, the leafhoppers (family Cicadellidae) attack all aerial parts of the plant whereas the planthoppers (family Delphacidae) attack the basal portions (stems). The leafhoppers and planthoppers (order Hemiptera) are sucking insects which remove plant sap from the xylem and phloem tissues of the plant. Severely damaged plants dry and take on the brownish appearance of plants that have been damaged by fire. Hence, hopper damage is called "hopper burn" (Fig. 3). The relative importance of leaf and planthopper pests varies from country to country, although the planthoppers—brown planthopper (BPH), *Nilparvata lugens*; the whitebacked planthopper (WBPH), *Sogatella furcifera*; small brown planthopper (SBPH), *Laodelphax striatellus,* and green leafhopper, *Nephotettix virescens*—affect most rice-growing areas in Bangladesh. These insects are severe pests in Bangladesh as well in Asia where they not only cause direct damage, by removing plant sap, but are also vectors of serious rice virus diseases, such as rice tungro virus transmitted by the green leafhopper, *Nephotettix virescens*, and grassy stunt virus transmitted by the brown planthopper, *Nilaparvata lugens.*

Fig. 3. Brown planthopper and its damaged symptoms observed in the rice field. A-C. Hopper burn observed in rice field; D. Nymphs settled on the base of the plant and sucking the sap; E. Fifth instar nymphs; F. Adult brown planthopper. Photo source: IRRI rice knowledge bank.

Defoliators

A large group of insects belonging to several insect orders feeds on rice leaves. Most common are the larvae and adults of beetles (order: Coleoptera), larvae of the order Lepidoptera and grasshoppers (order: Orthoptera). Defoliation reduces the photosynthetic capacity of the rice plant and thereby decreases yields. However, when feeding damage occurs early in rice growth, plants have the ability to compensate for damage by producing new tillers. Thus, rice plants in the actively tillering stage of growth can tolerate a certain level of leaf damage without any yield loss. Among the leaf feeders, rice leaf roller (RRL), *Cnaphalocrocis medinalis* becomes dominant and observed all over the country. The RLR causes longitudinal and transparent whitish streaks on damaged leaves and tubular folded leaves (Fig. 4). It often attacks rice in the early crop stages, causing highly visible leaf injury, but, because of plant compensation, the injury often does not translate into a yield loss (Graf *et al.*, 1992). There are at least three species of armyworm which attack rice in Asia. These are the rice swarming caterpillar, common cutworm, and the rice ear-cutting caterpillar.

Fig. 4. Rice leaf roller and its damage observed in the field. A. Damaged leaves caused by leaf roller larvae; B. Rolled leaf with threads; C. Egg laid by adult moth found in leaf; D. Leaf roller larva; E. Pupa; F. Adult moth. Images C-E were taken from www.crida.in.

Grain sucking insects

The rice bug, known for the foul odor produced by the scent glands on their abdomen, penetrates the developing grain with their sucking mouthparts and remove the white fluid referred to as "milk". Damage early in the development of the grain prevents the filling of the grain. Later attack results in "pecky rice" which is referred to as the condition of the grain after being sucked by rice bugs and the grain being subsequently stained by the bacteria or fungi which enter the puncture wounds. In some countries, the market price of pecky rice is reduced.

Ear cutter

The insect cuts the base of the panicles and those are left simply bend over of fall. Grass-green young larvae with dorsal stripes appear on the plants. Damage is often localized at the same time as the larvae migrate in the group between them. Ear-cutting caterpillar is commonly called armyworms that attack rice. There are at least three species of armyworm which attack rice in Asia. However, only the rice ear-cutting caterpillar, *Mythimna separata* is a moth of the family Noctuidae cut the panicle at the ripening stage of rice.

Scenarios of yield loss from rice insect pests

The average yield loss due to various insect pests in Asia where more than 90% of the world's rice is produced about 20% (Pathak and Khan, 1994). Any decrease in pest damage means a corresponding increase in needed rice production. A series of crop-loss assessment trials were carried out in the field by the Entomology Division of the BRRI against major insect pests from 1977 to 1979 have shown an average yield loss of 13% in the boro season, 24% in the Aus season, and 18% in the transplanted Aman (T. Aman) season (Alam *et al*., 1981). However, the amount of loss caused by insect pests varied to the estimated year and method (Table 2).

Potential yield loss

Yield loss can be greatly varied to insect pest species, rice variety, and geographic location. Table 2 shows yield loss due to insect pests estimated against different rice insect pests. Brown planthopper (BPH) can cause the highest yield loss in an outbreak area. The severity of the pest outbreak depends on the year. In an outbreak situation, insects like brown planthopper and rice hispa can increase loss by 44% and 62% respectively (Table 3).

Table 2. Annual national rice yield loss scenario due to insect pests in Bangladesh.

Loss (%)	Mode of estimation	Year of reporting	Reference	Comments
06.00	Insecticidal check method	1951	Alam, 1961	Field test
08.67	Insecticidal check method	1976	Catling *et al*., 1978	-
18.00	Crop loss assessment 1977-1979	1980	Alam *et al*., 1981	-
08.10	Survey estimation	1999	Islam and Catling, 2012	-
04-14	Literature review	2010	Mondal, 2010	-
01.00	Expert opinion on total production	2020	Kabir *et al*., 2020	Average annual national loss

Table 3. Yield loss estimation from research data under various experimental situations in Bangladesh.

Insect pest	Loss (%)	Year of reporting	Reference	Comments
Brown planthopper (BPH)	20-44	1985	BRRI, 1985b	Depends on season
Rice hispa	11-62	1985	BRRI, 1985a	Depends on season
Rice hispa	8.5-32.85	2012	Bari *et al.*, 2012	Depends on season and variety
Stem borer	15.0	1985	BRRI, 1985b	
Major insects	22-26	1985	BRRI, 1985a	Depends on season
Rice hispa	20-39	1982-1986	Karim, 1989	Depends on season
Leaf roller	4-11	1982-1986	Karim, 1989	-
Mealy bug	9-22	1982-1986	Karim, 1989	-
Ear-cutting caterpillar	9.0	1982-1986	Karim, 1989	-

Annualized national yield loss status

Climate change aggravates the outbreak of several insect pests including brown planthopper, leafroller, stem borer, and white backed planthopper. These insect pests cause significant economic loss. We assumedand fixed a generalized annual average loss1.0% of total national rice production in Bangladesh (Kabir *et al.*, 2020). However, differential reports on losses can found in the literature (Tables 2 and 3). Research results suggested that insect pests can cause 6-18% loss in Bangladesh. Based on the survey, this loss can be 4-8.1% in a normal year where pest outbreaks almost absent. However, the loss can be reached upto 44-62% in an odd year (when pest outbreak occurs frequently). Figure 5 depicts the rice yield losses incurred by insect pests in two different scenarios (survey and research reports).Therefore, we target to minimize this loss from 62% to 5% (Fig. 5) by implementing preventive methods such as stop insecticide application at the early establishment of rice, add flowering strips in the rice landscape, establish an early warning and forecasting system, use of balanced fertilizer, avoid cultivation of susceptible variety, growing resistant or tolerant varieties and follow crop rotation. Subsequent quick management options such as insecticidal treatment for specific insect pests should also be broadcasted through TV channels, and newspapers to check the abnormal situations in an odd year. Major efforts proposed above to minimize the economic loss in an odd year when pest outbreaks occur frequently and keep the loss upto 5%. These could be achieved by implementing proposed management technologies (summarized in Table 6).

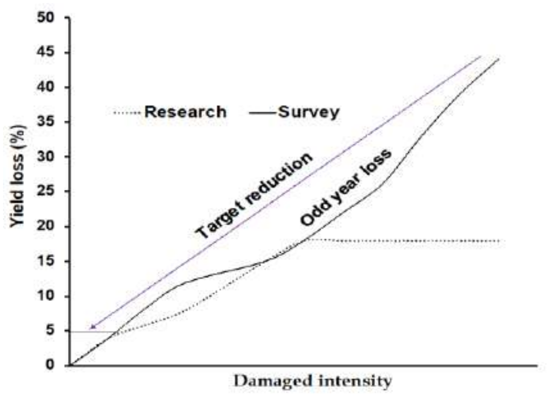

Fig. 5. Trends of rice yield losses in different scenarios. Losses incurred by insect pest estimated by researches, and surveys (outbreaks year). Blueline indicates the minimizing amount of loss by targeting different management technologies.

Action plan for three decades on reducing yield loss from rice insect pests

Tables 4a, 4b and 4c show the action plans to reduce the real yield loss in rice and prevent the abnormal outbreak of insect pests in the rice field. Elaboration of different strategic terms used in Tables 4a, 4b and 4c is enlisted in Table 5. According to action plans enlisted in these Tables, we briefly described the important core insect pest management approaches. The following approaches will be implemented sequentially during the next three decades from 2021-2050.

Table 4a. Action plant for location, variety, and insect pest specific smart management for a period for 2021-2030. Elaboration of each term used in this Table is listed in Table 5.

Insect pest	Location, variety and insect pest specific smart management									
	Period: 2021-2030									
	Research and development phase							Dissemination phase		
	Primary		Intermediate		Maturation		Follow up	Step-1	Step-2	Step-3
	IBR	YL-EST	Mtg-FWK	EPI	Cali-Valid	Sm-Mtg	CM	Train	Demo	EW
Brown planthopper										
Stem borer										
Leaffolder										
Green leafhopper										
Gallmidge										
Rice hispa										
White backed planthopper										
Rice bug										
Thrips										
Caseworm										
Ear-cutting caterpillar										
Rice mealy bug										
Rice whorl maggot										
Rats										
Any other emerging insect pest										

Table 4b. Action plant for location, variety, and insect pest specific smart management for a period for 2031-2040. Elaboration of each term used in this Table is listed in Table 5.

Insect pest	Location, variety and insect pest specific smart management Period: 2031-2040									
	Research and development phase							Dissemination phase		
	Primary		Intermediate		Maturation		Follow up	Step-1	Step-2	Step-3
	IBR	YL-EST	Mtg-FWK	EPI	Cali-Valid	Sm-Mtg	CM	Train	Demo	EW
Brown planthopper										
Stem borer										
Leaffolder										
Green leafhopper										
Gallmidge										
Rice hispa										
White backed planthopper										
Rice bug										
Thrips										
Caseworm										
Ear-cutting caterpillar										
Rice mealy bug										
Rice whorl maggot										
Rats										
Any other emerging insect pest										

Table 4c. Action plant for location, variety, and insect pest specific smart management for a period for 2041-2050. Elaboration of each term used in this Table is listed in Table 5.

Insect Pest	Location, variety and insect pest specific smart management									
	Period: 2041-2050									
	Research and development phase							Dissemination phase		
	Primary		Intermediate		Maturation		Follow up	Step-1	Step-2	Step-3
	IBR	YL-EST	Mtg-FWK	EPI	Cali-Valid	Sm-Mtg	CM	Train	Demo	EW
Brown planthopper										
Stem borer										
Leaffolder										
Green leafhopper										
Gallmidge										
Rice hispa										
White backed planthopper										
Rice bug										
Thrips										
Caseworm										
Ear-cutting caterpillar										
Rice mealy bug										
Rice whorl maggot										
Rats										
Any other emerging insect pest										

Table 5. Elaboration of different strategic terms used in Table 4a, 4b and 4c.

Programme	Phase	Stage	Action
Research and Development	Primary	IBR*	○ Identification (symptom & the insect pest) ○ Biology (for genetic ID & reproductive behavior) ○ Rearing (mass rearing technique)
		YL-EST	○ Yield loss estimation (by insect pest severity scale)
	Intermediate	Mtg-FWK	○ Managementframework (considering all possible options, based on current knowledge)
		EPI*	○ Epidemiology (based on local conditions, not just on information from the literature. Finding the exact driver(s) of the insect pest epidemics
	Maturation	Cali-Valid	○ Calibration and Validation (testing every component of the management framework by location & variety; applying all tools)
		SmMtg	○ Smart management package developed to be acceptable to farm adoption
	Follow up	CM	○ Continuous monitoring to keep on notice if changes happening on smart management package, e.g., variety tolerance; reaction to new varieties
Dissemination	Phase-1	Train	○ Training (DAE officers and lead farmers)
	Phase-2	Demo	○ Demonstration (in the location of insect pest risk)
	Phase-3	EW	○ Early warning system-based insect pest alert communicated to farmers

*IBR: Identification, Biology and Rearing; EPI: Epidemiology; Cali-Valid: Calibration and Validation; CM: Continuous monitoring; SmMtg: Smart management; Train: Training; YL-EST: Yield loss estimation; Demo: Demonstration; EW: Early warning; DAE: Department of Agricultural Extension

Approaches to be followed to address insect pest management

Stop spraying at early growth stage of rice

Currently, insect pest management solely depends on chemical insecticide which has a tremendous impact on the environment, animal, and human health. Farmers usually apply insecticides 2-4 times in a season in their rice fields. Most of the farmers of our country started to spray pesticide at an early stage of rice and continue upto flowering for securing their crops. The application of these insecticides can't protect against the real loss of production in our country. Moreover, this chemical insecticide hampers the natural regulation of insect pests in the rice field and enhances the production cost.

At the early growth stage of rice, neutral insects are the food source of the predators due to the lack of insect pests (Yu *et al*., 1999). The number of Chironomid midges can be up to 4.5 million per hectare in the paddy fields, and 80% of them exist in the early growth period of rice. In this period, Chironomid midges provide plenty of food sources for predators. In the later period of rice, the number of Chironomid midges is decreased, and the predators can feed on insect pests (Wu *et al*., 1994; Li *et al*., 2010). In the early rice paddy field with low application of insecticides, plenty of saprophytes can also be an alternative food for the predators.

Application of insecticides at the early period of rice will kill natural enemies and neutral insects, and induce the occurrence of insect pests like rice planthoppers and leaf folders in the later period of rice. Predators, parasites, and parasitoids provide a vital role in checking pest build-up in the rice field. To date, 175 predators and 192 parasitoids are identified at the rice field in Bangladesh which provides natural control of pest outbreaks. Here we propose innovative approaches that might help to enhance productivity by 0.50% in rice. In this approach, firstly farmers are advised not to apply insecticide in the rice field upto 30-40 days after transplanting. During this tenure, natural pest control agents boost up and regulate the abnormal growth of insect pests in crop fields. However frequent field visits (7-10 days interval) are suggested to detect any infestation at a significant level. This will limit the chance of production loss.

Web GIS based information visualization for pest infestation and management

To reduce the loss due to insect pest infestation, careful pest management is crucial. In order to ensure the information is delivered to all farmers, it is proposed to visualize the information via the web geographical information system. The map view is important to help distinguish one place from another and then to make an emergence action to prevent the separation of infestation to the nearest paddy plant. The web geographical information system for pest infestation areas is produced by using ArcGIS online. We will install ArcGIS online in BRRI which produces web geographical information system for pest infestation area. It will visualize the information and deliver to all farmers and other stakeholders who are directly and indirectly involved in rice production in Bangladesh. Figure 6 shows flow diagram web GIS system. The map view is important to help differentiate one place to another and then to take urgent action to prevent the spread of the pest to the nearest rice plant. After getting information on insect pest infested areas, localized application of chemical insecticide for rapid management must reduce pesticide use in Bangladesh. This system also ensures safe food production and reduce national pesticide consumption.

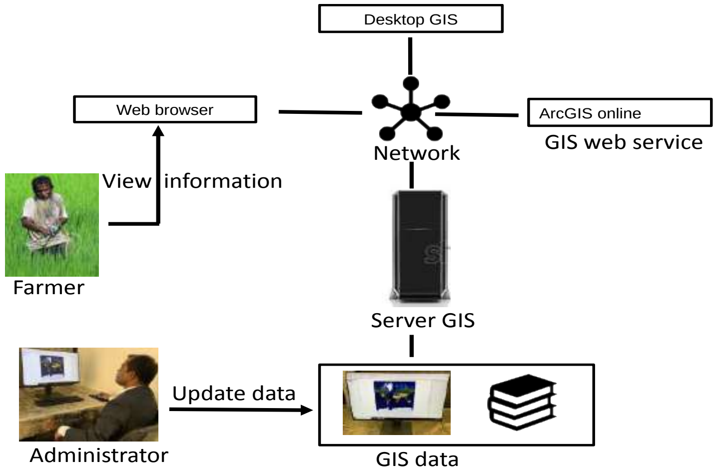

Fig. 6. Flow diagram for web GIS information visualization for insect pest infestation. The model information adopted from Laajis *et al*., 2016 and has been modified by authors.

Conservation of natural enemies in rice field

During the last decade, witnessed crop losses caused by pests especially brown planthoppers at an unprecedented scale (Heong *et al*., 2015). Resistant varieties and formerly effective insecticides are failing because of adaptation in pest populations, making these insects ever harder to control and threatening food security. A viable new, ecologically-based approach that will put rice production on a more sustainable and profitable footing. Our previous studies showing that crop-border plantings suppress rice pests, reduce insecticide use, boost yield and increase profit to put national/global rice production on a more profitable and sustainable footing (Gurr *et al*., 2016; Ali *et al*.,2019). Selecting flowering plants that are well-suited for growing on the earth banks beside rice crops. These provided refuge and nectar for beneficial insects that in turn attack pests. Carefully-selected flowering crops on the earth banks in the vicinity of rice fields suppress potentially devastating pests of rice crops, thus providing valuable ecosystem service (Fig. 7A). This flower power' approach effectively promotes beneficial insects that check pest build-up. Farmers can grow flowering plants in rice bunds around the field especially during the dry season and stop insecticide application in their field.

Fig. 7. Flowering plants were grown on the bunds in rice plots to provide resources for biocontrol agents, especially parasites/parasitoids, in rice landscapes. (A) Flowering plants (sunflower, marigold, cosmos) grown on bunds during Boro 2017–18. (B) Sesame plants grown on bunds at T. Aman 2017, BRRI, Gazipur.

Additionally, some border crops can be used as vegetables, or provide fruits or other seeds which also can be harvested to provide a dual income and add to the diverse diets and livelihoods (Fig. 7B). Levels of pest control would be improved compared with conventional practice to the extent that host farmers reduced the numbers of insecticide sprays by more than three-fold (Gurr *et al*., 2016; Ali *et al*., 2019). Significant higher percentage of egg parasitism of BPH, WBPH, stem borer, and rice hispa was found (Fig. 8). This result indicates that a significant highernumber of parasitoids including *Anagras*, *Trichograma zahiri* and *Trichgrama chilonis* prevails in rice field where nectar rich flowering plants are grown that ultimately reduce insect pest number in the field (Ali *et al*., 2019). Even better, rice yield improved by 5% in the flower-bordered rice crops (Gurr *et al*., 2016). Farmers will be able to harvest these secondary crop borders at the end of the season to diversify diets and as a secondary income that - together with reduced spraying costs and boost rice yield increased economic advantage by 7.5% (Gurr *et al*., 2016).

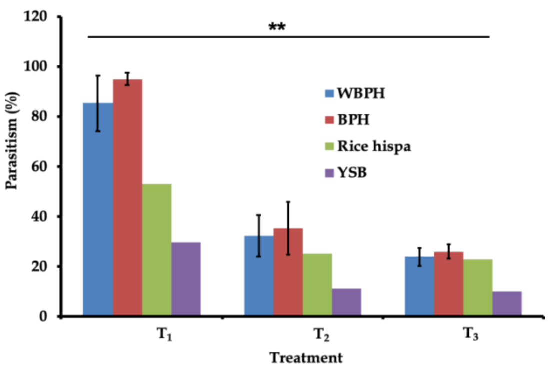

Fig. 8. Percent egg parasitism of brown planthopper (BPH), white backed planthopper (WBPH), yellow stem borer (YSB) and rice hispa egg in different treatments (T_1 = Flowering plants grown on rice bund, T_2= Prophylactic insecticide use, and T_3= Control (No insecticide and no flowering plants) in Boro season. Error bars indicate standard errors. Data were recorded by egg bait trap method. ** indicates significant at the 1% level.

Conservation of natural enemies in rice landscape has a sound background for pest management through ecological engineering and has a great opportunity to accept in our society. Ecological engineering has recently emerged as a paradigm for considering pest management approaches that are based on cultural practices and informed by ecological knowledge rather than on high technology approaches such as synthetic pesticides and genetically engineered crops (Gurr *et al*., 2004). Thus, ecological engineering emerges as a new direction for agricultural pest management (Gurr *et al*., 2014). Bunds (levees of the terrestrial area surrounding the fields) build an extensive network that connects rice fields. Typically, they have sparse seminatural vegetation that can potentially offer alternative food resources or refugia to natural enemies (Way and Heong, 1994) and likely facilitate the ability of rice arthropods to move through the rice agroecosystem. For example, specific egg parasitoids that cause high mortality of pest planthoppers occur in wild grasses on rice bunds (Yu *et al*., 1996). Some spider species, which commonly inhabit bund vegetation, are known as early colonizers of newly established rice crops (Sigsgaard, 2000).

Seeding or planting flower strips on these bunds (Fig. 7) enhance parasitoids as well providean important food source for honey bees. Because the later are highly valued in rural communities, it is easier to convince farmers not to spray insecticides, which in turn also leads to less disturbance of the ecological network within and along with rice fields. As an additional benefit, landscapes are perceived as more beautiful. The involvement of farmers in these ecological engineering activities enhances the acceptance and effectiveness of landscape-wide management of biocontrol and other ecosystem services (Westphal*et al*., 2015).

Insect pest management in rice field by chemical pesticide

To minimize the pest number in the crop field and keep the loss upto 5% in an odd year, subsequent quick management option such as chemical pesticide is also required with preventive measures. Besides this, there are many options for controlling pests, and many of these options are tailored to specific pests or problems. Integrated Pest Management (IPM) is a pest control approach that uses the least toxic methods first. IPM includes common sense methods based on scientific knowledge of the pest and its habits. Methods often include removing pests' food source, blocking their entry into an area or building, using beneficial organisms, and the judicious use of pesticides. In IPM, pesticides may be used as a last resort, when non-chemical controls have failed, and the pest problem is serious enough to require chemical control. This would be highly recommended when an abnormal situation arises in any crop field. However, before deciding to spray chemical insecticide in the crop field, we must need to consider the damaging level in the field. We can tolerate the yield loss caused by different insect pests at a specific infestation level (called economic threshold level, ETL). When the infestation level (deadheart) exceeds the 10-15% dead heart caused by yellow stem borer, a significant loss will have occurred, and control measures should be initiated immediately. The insect pest specific recommended chemical insecticides would be sprayed immediately at an abnormal situation (outbreak of pest in the field). In this situation, farmers are also suggested to take advice from pest management experts (list are available on BRRI website; www.brri.gov.bd). These professional experts may offer assistance at different stages of your pest control process.

The negative impacts of agrochemicals application in agriculture and malaria eradication programme have been reported and documented over the years. The major problems associated with agrochemicals are negative impacts against non-target organisms, the resurgence of secondary pest populations, the development of resistant organisms, and the expense. Human health and environmental impacts arise from pesticides due to lack of phyletic specificity, pesticide resistance due to limited sources in the bioactivity of pesticides are the major problems which have been associated with the application of chemical pesticides. Moreover, consumers and the food chain alike are increasingly demanding food products that are residue-low or residue-free and produced in more sustainable ways.

Table 6. Management interventions in Bangladesh for achieving the target (rice yield loss reduction) by 2050.

Intervention	2020	2030	2040	2050
Stop insecticide spray at early crop establishment stage	Limited scale	At least 25% farmers follow	At least 50% farmers follow	At least 60% farmers follow
Early warning system	Nil	Start limited area	Deliver to 50% farmers	Deliver to 60% farmers
Web geographical information system for pest infestation area	Nil	Start limited area	25% farmers will get this information	25% farmers will get this information
Conservation of natural enemies	Limited in experimental field	10% farmers will practice	25% farmers will practice	40% farmers will practice
Resistant variety developed using CRISPR Cas9	Nil	10% farmers will produce this variety	20% farmers can produce this variety	40% farmers can produce this variety
Gene drive BPH population develop	Nil	Release in BPH outbreak area	40% area can be covered	40% area can be covered
Chemical control	Exist	Localized application only in outbreak field	Localized application only in outbreak field	Localized application only in outbreak field

To avoid such dramatic impacts and to get out of this deadend, alternative pest control strategies must be developed to deliberate cost efficiency, low possibility to develop resistance, less negative impact on the environment. To address this problem, several sequential strategies are proposed here that ensure to reduce the losses caused by insect pests in rice and promote safe food production in Bangladesh. Table 6 enlists the all management interventions with a specific target timeline.

Insect resistance breeding and functional mechanism

Resistant rice cultivars are being sought as an effective integrated pest management tactic for rice production. A major objective of rice breeding programs is to incorporate insect resistance into modern cultivars (Zhang 2007). Insect resistance in plants involves a gene or suite of genes that produce a product or products that inactivate or otherwise disable the target insect. Resistant rice cultivars alter the physiology and behavior of insects, which in turn affects the insects' susceptibility to chemical and biological control mechanisms (Li et al., 2014). Transgenic rice harboring an exogenous Bt gene (encoding an insecticidal toxin produced by *Bacillus thuringiensis*) has been used to breed insect-resistant rice. The Bt gene is effective against the stem borer and leaf roller chewing insects, but not against piercing and sucking insects, such as brown planthopper (BPH).

Over the past several decades, great progress has been made in the screening of insect-resistant rice germplasm, identifying resistance genes, and uncovering the molecular mechanisms of host resistance. The use of resistance genes and other efforts to breed "Green Super Rice", a high-yielding, good quality, insect resistant ideal rice variety, will increase the profitability of rice production and contribute to a healthy ecological environment. This review addresses research advances underpinning strategies to improve the resistance of rice to insect pests. We need to focus on the genetic and molecular mechanisms of insect resistance and the practical application of gene technologies to rice breeding for improved insect resistance, which represent the development trend of rice insect resistance breeding and also provide a reference for other crops.

Marked progress has been made in recent years to map, clone, elucidate the underlying resistance mechanisms, and leverage insect resistance genes in rice, allowing for a better understanding of the molecular basis of such resistance and facilitating efforts to breed insect-resistant rice varieties. However, many challenges remain in our efforts to achieve reliable insect resistance in rice. As rice resistance to insects in rice coevolved with the insects themselves, insect resistance genes are more frequent in regions of the world where pests are more common. Therefore, efforts to more thoroughly screen rice germplasm resources in these regions will provide the opportunity to identify additional insect resistance germplasm. The 3000 Rice Genome Project has resequenced a core collection of 3000 rice accessions from 89 countries to an average sequencing depth of 14× (The 3000 Rice Genomes Project 2014). This and other high-throughput sequencing efforts and related SNP data offer an opportunity to leverage genome-wide association studies to detect and exploit insect resistance genes. The findings of such studies offer ways to better analyze allelic variations and distributions in insect resistance genes within the germplasm, enabling studies of their origins and evolution.

Over the past decade, rapid technological advances have been made in the discovery and analysis of plant and insect genomes, transcriptomes, proteomes, and secretomes. These techniques have provided the impetus to identify putative insect effectors, clone insect resistance genes, and reveal the signaling pathways and key components of plant–insect resistance signals. However, there is still a major gap in our understanding of insect-plant interactions. No effectors corresponding to the R gene have yet been identified, although 14 insect resistance genes (encoding LecRK and NLR proteins) have been cloned in rice. Similarly, although three effectors have been identified from Hessian flies, the corresponding R genes have not been cloned. The roles of hormone signaling and the corresponding regulatory genes involved in insect resistance in rice have been discovered, and a preliminary regulatory network has been constructed (Du et al. 2020). However, the roles of insect resistance genes in this network are still unclear. Furthermore, no substances that are lethal to insects have been identified in rice. Studies aimed at addressing these issues will provide a more thorough understanding of how these resistance proteins recognize and mediate effector-triggered signaling and immunity against insects.

Because multiple insect pests are simultaneously present in the field, the indiscriminate use of insecticides for pest management is more practical, economical, and effective than growing insect-specific resistant rice varieties. Therefore, insect resistance breeding must involve the incorporation of broad-spectrum resistance genes to minimize the investment in crop management, making this technique more suitable for meeting the expected return on investment of rice farmers in the future. Now, MAS has already been used to pyramid multiple insect resistance genes to cultivate durable, broad-spectrum insect resistance rice. The following approaches need to be applied for future insect resistance breeding in Bangladesh.

1. Marker-assisted selection
2. Molecular understanding of insect resistance
3. Identification and mapping insect resistance gene
4. Cloning and characterization of insect resistance genes in rice
5. Resistance associated signal transduction in rice
6. Insect defense related metabolites
7. Plant mediated RNA interference.

Promising advanced tools for insect pest management

Development of insect-resistant variety by CRISPR Cas9

Developing resistance variety is the most economic and environment friendly avenue to combat insect pests and reduce loss. In addition modern breeding approaches, new emerging technologies such as CRISPR Cas9 gene editing to convert insect susceptible alleles to insect resistance alleles, as well as altering the levels of specific secondary metabolites in vivo, provide the potential to design crops that can be patched in real time to combat evolving pests. Furthermore, these emerging technologies will be invaluable for uncovering the roles of insect effectors and plant target proteins in the regulation of plant immunity. In rice, the gene *CYP71A1* encodes a cytochrome P450 monooxygenase, which exhibits tryptamine 5-hydroxylase enzyme activity, catalyzing the conversion of tryptamine to serotonin. In *CYP71A1* knockout mutants, prevention of serotonin synthesis increases resistance to rice blast *Magnaporthegrisea* but increases susceptibility to rice brown spot disease *Bipolaris oryzae*. Furthermore, Stripped stem borer (SSB) could induce serotonin synthesis in rice plants potential role of serotonin in the regulation of insect resistance. In susceptible wild type rice, planthopper feeding induces biosynthesis of serotonin and salicylic acid (SA), whereas in mutants with an inactivated CYP71A1 gene, no serotonin is produced, SA levels are higher and plants are more insect-resistant (Lu *et al.,* 2018). Addition of serotonin to the resistant rice mutant and other BPH-resistant genotypes results in a loss of insect resistance (Lu *et al.,* 2018). Similarly, serotonin supplementation in an artificial diet enhances the performance of both insects. Furthermore, SA depresses CYP71A1 expression and thus serotonin production, and serotonin represses expression of SA biosynthesis genes and thus SA synthesis, suggesting a mutual negative feedback mechanism regulating the differential accumulation of these two hormones. Brown planthopper, *Nilaparvata lugens* (Homoptera: Delphacidae) and yellow stem borer, *Scirpophaga incertulas* (Lepidptera: Pyralidae) are major insect pests in Bangladesh cause serious yield losses in rice. We will develop these insect pests resistant rice varieties using CRISPR Cas9 (clustered regularly interspaced short palindromic repeats) system with a similar yield to current mega cultivars by inhibiting serotonin synthesis in rice plants.

Use of drone for insect pest management in rice field

Most of the farmers of our country are illiterate and ignore the vigilance of crop fields regularly. Therefore, they only identify the field when losses have already been done. Early detection of insect pest infestation in the field will limit the production loss. So, the effort to early detection of insect pest infestation will reduce the production loss in Bangladesh. We will propose to monitor rice fields using a specialized drone (drone with insect monitoring tool) that will help to early detection of insect pest infestation. We will fly the drone from each Upazila Agricultural Office to a specific rice field within the Upazila peripheryat 7-10 days intervals to monitor and making the decision to spray or not to control insect pests. We have a light trap to catch insect pests at every night in the rice field. Our strategy to attached this light trap with the drone and fly them to the rice field at 15 days intervals (it may be 10-15 days). When the drone will reach a target rice field, light trap will be started and attract to catch insects. After 2- 3 hours, the drone will be withdrawn from the rice field and counted the caught insects. The recorded insect pest will be analyzed and used to decideto control them in the field. If the analysis results indicate that pest control measures need to be initiated and farmers could be advised to apply control. This process will identify earlier any infestation that can cause serious losses later.

Application of gene drive technique for rice insect pest management

Gene drives will replace all conventional insect population control strategies, such as the Sterile Insect Technique, which is used to control fruit flies in Australia and mosquitos around the world. Because gene drive strategies will not require that insects are continually bred and released from factory scale insectaries in an attempt to inundate pest populations.The synthetic gene drives spread themselves, potentially doubling every generation, so that only relatively small numbers of gene-drive bearing insects would need to be released to inoculate a pest population. By 2030, we aim to develop a male population of a brown planthopper using the gene drive technique which reproduces the only son when mates with females in nature. If successful, this research will pave the way pest management approach without damaging diversity and the environment ultimately leading to a next generation crop protection approach.

The overall goal of this method is to apply for recent advances in gene editing (CRISPR Cas9) to produce a suitable treatment to suppress insect pest populations from rice crops. The central hypothesis of the proposed research is that 'gene drive' bearing male insects will be released so that all mated females will only produce males, thus reducing the population of females, and thereby reduce the fecundity of the entire brown planthopper (hereafter BPH, *Nilaparvata lugens*, the most rice damaging insect pest) population. In this method, we will develop a male population of a BPH using a gene drive technique, which will result in all offspring post mating being male, no females.

In turn, implementing this "BPH-All-male", gene drive treatment could significantly reduce use of pesticides, while increasing biodiversity in the ecosystem, and enabling a larger benefit from beneficial arthropods (predators, parasitoids, and pollinators). Rice produced without pesticide will grantee export quality and consumer satisfaction.

In BPH, two genes including *Nldsx* and *Nltra2* are found to play important roles during the sex determination in the BPH; moreover, the sex-specific splicing of *Nldsx* is common, with *Dmdsx* exhibiting different repeat nucleotide sequences on the female-specific exon (Zhuo *et al*., 2018; Zhuo *et al*., 2017). The *NIFmd* (female determinant factor) is involved in the sex determination cascade of BPH. Knock out of *NIFmd* gene from BPH produces only male population (Zhou *et al*., 2019). This result indicates that inhibition of *NIFmd* gene in BPH reproduces only male population when these male mate with other female available in field, their next generation will be all male also.Moreover, *NlFmd* homologs play roles during the sex determination of the white-backed planthopper (*Sogotella furcifera*), and the small brown planthopper (*Laodelphax striatellus*) (Zhuo *et al*., 2019).

We will use gene drive to produce BPH male using CRISPR Cas9 genome editing system. Figure 9 shows the design (mechanism) of gene drive approach that will be adopted in this project. The RNA guide will incorporate sequences to target a *NIFmd* gene that is useful to clearly identify if the system is working. Gene may be the sex-specific transcript of *NIFmd* (NIFmd-F) encodes an arginine/serine, and proline-rich protein that is essential for female development (Zhuo *et al*., 2019). This system may have the following components: (1) Cas9 endonuclease required for DNA cleavage, (2) sgRNA containing the 20 base target sequence for the sex-specific transcript of *NIFmd* (NIFmd-F) that is essential for female development as well as the region that forms a complex with the Cas9 nuclease, and (3) the 'cargo' gene controlling the desired trait pass generation to generation. Free online tools can be used to search the coding region to identify an appropriate 20bp target sequence that is downstream from a protospacer adjacent motif(PAM) sequence that will be cleaved by the Cas9 nuclease.

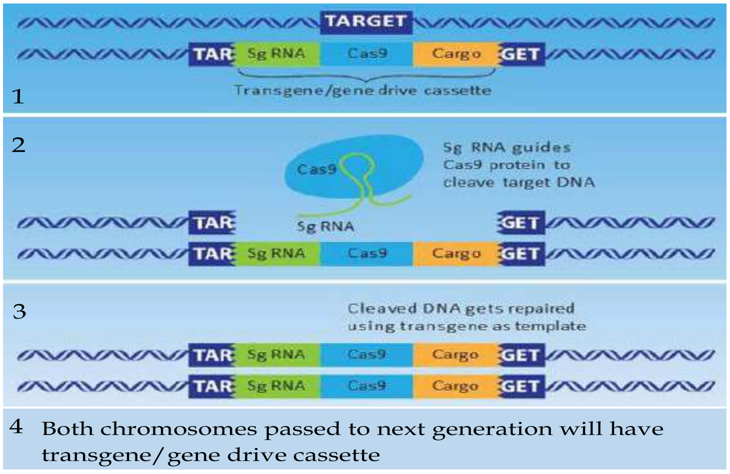

Fig. 9. A synthetic CRISPR Cas9 gene drive. Sg RNA is the guide RNA, Cas9 is an endonuclease which cuts the DNA and cargo is the desired genetic material added. When all three elements are present in a gene drive cassette this ensures that each chromosome will have the desired cargo and will be inherited by the next generation thereby spreading. The figure is adapted fromwww.science.org.au.

Gene drive mechanisms

Recent advances in gene editing tools allow organisms to be edited much more efficiently and more accurately than previously possible. Scientists can now harness gene drive mechanisms which were previously merely theoretical to control or alter natural populations. While not a gene drive tool in its own right, clustered regularly interspaced short palindromic repeats of base sequences (CRISPR), can be used as part of a system to produce a synthetic gene drive.

When CRISPR is paired with a guide RNA and with specific proteins, such as Cas9 (CRISPR associated protein 9) that cuts DNA, it can be used to efficiently edit genetic material. In natural prokaryotic systems, CRISPR/Cas9 is produced by host bacteria to remove viral DNA by targeting repeats associated with viral insertions, as a kind of immune system to combat infections. For gene editing purposes, the Cas9 protein and guide RNA are injected into the cell to cut the DNA at a sequence complementary to the RNA guide. For synthetic gene drives, the target organism is transformed with a construct that includes the gene for the Cas9 protein, a guide RNA that is complementary to the sequence at the insertion site, and the 'cargo' gene controlling the desired trait (Fig. 9). The guide RNA directs Cas9 to produce a double stranded cut in the DNA at the target site in the other chromosome. This triggers the cell's repair mechanism, which copies the entire construct (Fig. 9). If germ cells are targeted, the new sequence can then be passed on to offspring ensuring the editing changes can occur in each generation. A CRISPR-based gene editing technique are used in all four synthetic gene drive proof-of-concept studies in 2015 and applied to be generated laboratory-based gene drives in yeast *Saccharomyces cerevisiae* (DiCarlo *et al*., 2015), fruit fly *Drosophila melanogaster* (Gantz and Bier, 2015) and two mosquito species *Anopheles stephensi* (Gantz, 2015) and *Anopheles gambiae* (Hammond *et al*., 2018).

Implementation strategy

- Training of farmers and sub-assistant agricultural officers (SAAO)would be conducted to motivate them to stop insecticide application at the early establishment stage of rice.
- Early warning systems of insect pest infestation in the rice field would be developed and delivered to farmers at local scales. In addition, the web geographical map for pest infestation area is produced by using ArcGIS online and information is delivered to all farmers via the web geographical information system.
- Motivate farmers to conserve natural enemies in the rice field through an ecological engineering approach. Broadcasting via national media like TV/radio or newspapers can motivate farmers to conserve natural enemies.
- Develop and deliver brown planthopper resistance rice varieties (developed through CRISPR Cas9 approach) to farmers.
- Gene drive brown planthopper (BPH) population will be developed using CRISPR Cas9 and release into the outbreak area. Released gene drive male BPH mates with female in the field and subsequently replace all females.
- Chemical insecticides are also suggested to apply as the last option when an abnormal outbreak of pest occurs.

CONCLUSION

Most of the approaches described here ensure safe food production in Bangladesh. Rice fields need to be monitored at 7–10 days intervals for checking levels of pest infestation. Field monitoring helps farmers best control their rice pests. Refraining farmers from applying insecticides to rice fields before 30-40 days after transplant (DAT) enhances natural enemy activity to check the build-up of pest populations. Practicing the need-based application of insecticide also significantly reduces the total pesticide load in rice fields. In addition, recent advent genetic techniques such as gene drive and developed resistant variety by applying CRISPR Cas9 need to be adopted to ensure safe food production in Bangladesh. Based on the discussion, it is concluded that currently, farmers should avoid prophylactic measures, and rather farmers monitor their crop fields at 7–10 days intervals up to the flowering stage and prepare to adopt more advanced techniques such as gene drive. All of these will reduce pesticide use in agricultural landscapes and improve environmental quality.

RECOMMENDATION

- Developing an early warning system on insect pest infestation and inform farmers.
- Developing digital platform for reaching early warning signals and smart pest management systems to farmers.
- Making research investments and policy changes that emphasize the development of pesticides and application technologies that posereduced health risks and are compatible with ecologically based pest management.
- Promoting scientific and social initiatives to develop and use alternatives to pesticides more competitive in a wide variety of managed and natural ecosystems.
- Increasing the ability and motivation of agricultural workers to lessen their exposure to potentially harmful chemicals and refines worker-protection regulations and enforce compliance with them.
- Reducing adverse off-target effects by judicious choice of chemical agents.
- Implementing precision insecticide application technologies.
- Exploring more recent advent genetic tool for effective sustainable management of rice insect pests in Bangladesh.

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AUTHORS' CONTRIBUTION

MPA, MUS, and MSK generated idea; MUS and MSK coordinated the research; MPA developed methodology; MPA, BN and MTK provided scientific insights; MPA gathered data, carried out analysis and synthesis; MPA did the writings for all versions of the manuscript; BN, MTK, 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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Strategy for Rice Disease Management in Bangladesh

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ABSTRACT

Disease is one of the most limiting biotic factors that affects rice production worldwide. In Bangladesh, there are 10 rice diseases considered as major, which cause economic loss in farmers' fields. Therefore, the aim of this article is to explore all the feasible avenues of technology deployment on rice disease management to restrict the disease infection at minimum level and thus minimize economic loss. The article is generated using data and/or infromation from published and unpublished works and incorporating authors' experience. It is evident that periodically (odd year) a disease outbreak or epidemic occurred in Bangladesh such as blast. Under epidemic situation, research findings estimated a yield loss of up to 98% at the highest disease severity level of infection of blast. On the other hand, field survey indicated the highest of 65.4% yield loss from severly infected field with the disease. To overcome the epidemics in odd years and to keep the loss under economic threshold level, it is necessary to undertake preventive measures such as planting of resistant or tolerant varieties, use of disease-free seeds from healthy plants, use of balanced fertilizer where applicable, and following feasible crop rotations. Currently, it is urgent need for developing strong and precise weather-based disease-risk forecasting system at least one week's lead time based on real-time weather data. Subsequent quick management options such as disease-specific fungicidal treatment should be communicated to all stakeholders using fast-delivery media such as TV channels and SMS could be efficient and effective ways to address the disease outbreak under epidemic situation. To address annualized yield loss, it is suggested to execute interventions like effective training to the root level (both for farmers and extension personnel) and conducting demonstration in farmers fields, regular field monitoring, digitalization in disease management sector, revive indigenous technologies as appropriate, and improving rice production system. To continously improve rice disease management sector, this paper has proposed an innovative action for three decades through to 2050 under the banner 'Location, Variety and Disease Specific Smart Management' on research, development and extension.

Key words: Rice disease, effective training, monitoring, digitalization, epidemiology

INTRODUCTION

Global rice production is expected to face more challenges in the coming years, and Bangladesh is predicted to be exposed to more of those tricky situations. Those challenges include different bio-aggressors especially diseases of rice crop. Rice is anticipated to continue to be the major human staple food crop well into the 21st century (Zeigler *et al*., 1994). Therefore, we must think of the rice security for the generations of the next decades. And, to meet the demand, we must rethink about the efforts to reduce the risk of the losses caused by different diseases for sustainable rice production. It has been stated that the development and release of high input loving, high yielding cultivars are altering the micro-ecobalance, resulting in severe disease problems (Shahjahan, 1993). Quantified annual yield losses based on surveys due to a combination of rice diseases ranged from 1 to 10% in Asia (Rice diseases workshop, 2014). Unfortunately, there is no precise and updated yield loss data accounting for rice diseases for the whole nation. Our projected clean rice production for 2050 has been set as 40.40 million tons (Kabir *et al*., 2015). To achieve this estimated production and minimize the losses caused by diseases, it would be necessary to fully utilize existing resources, as indicated in Kabir *et al*. (2020). The farmers of Bangladesh

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are the catalyst to make the country self-sufficient in food production. Therefore, it is pertinent to transmit all of our knowledge, information, and technologies to the farmers to get maximum return from rice production.

With the above background, this article undertook three specific objectives in relation to rice diseases in Bangladesh: (i) presentation of their changing status, (ii) highlighting the scenarios of yield loss associated with the diseases, and (iii) development and mapping the action plan for three decades on reducing yield loss from the diseases.

METHODOLOGY

The study contains the information mostly conceptualized by the authors. Most data and some ideas were derived from secondary sources, which have been appropriately cited. A number of works (Shahjahan, 1993; Thurston, 1994; Shen and Lin, 1994; Teng, 1994; Islam and Catling, 2012; Arya, 2018) were used for reviewing purposes. The published and unpublished data on yield loss for four diseases - sheath rot, sheath blight, false smut, and blast - presented in graphs in this paper were collected either from farmers' fields or research fields are mostly from authors own research findings data. A simple diagram has been proposed on networking between farmers' field problems and researchers. The idea for this was burrowed from Rhoades and Booth (1982). The baseline data for yield loss were estimated by group discussion. The set of disease data were derived from farmers' demonstration those were conducted by plant pathologists of the Plant Pathology Division in Bangladesh Rice Research Institute (BRRI). Those data were sourced from presented and/or published in BRRI annual review research workshops.

RESULTS AND DISCUSSION

Status of rice diseases in Bangladesh

The disease that causes economic loss in rice yield is defined here as a 'major' disease, while the one does not cause significant economic loss as 'minor'; the definition is more as subjective than quantitative. The identified rice diseases in Bangladesh have increased from 24 (1987 report) to 32 (2016 and 2018 reports) (Table 1; Appendix 1). Out of 32 diseases, 22 are caused by the fungus, six by nematodes, three by bacteria, and one each by virus and mycoplazma (Appendix 1). Currently, 11 diseases are recognized as major; this number was 10 in 1987 (Table 1) and 1993 (Shahjahan, 1993). Eight diseases (alphabetically, bacterial leaf blight, bakanae, blast, brown spot, sheath blight, sheath rot, ufra and tungro) have remained as major during 1987-2016 period. Two diseases (alphabetically, leaf scald and stem rot) that were classed as major in 1987 have currently been downgraded to a minor. On the other hand, three diseases (alphabetically, bacterial leaf streak, false smut, and seedling blight) are presently graded as major that were considered as minor in 1987. A recent study on the potential impact of climate change on crop diseases in Bangladesh showed the continued risk of major rice diseases but a likely monthly- shift in their incidence under given future climate scenarios (Salam *et al*., 2019).

Yield loss scenarios due to rice diseases in Bangladesh

Shahjahan (1993) states, "There is little quantitative data available on crop losses due to diseases on a regional or country scale in Bangladesh. Available reports are based on estimates because of the apparent lack of proper crop loss assessment methods and monitoring of pest and disease incidence in the country". The same author further mentions that the loss assessment due to diseases is difficult because of the following reasons:

i) The yield or production in absence of the diseases is not known;

ii) Loss occurs only in a limited area, which must then be projected to estimate the loss over the whole crop;

iii) Loss may occur in one year or one season and needs to be averaged over several years; and,

iv) Loss may be on selected high infection, after artificial inoculation of selected crop timing.

Table 1. Rice diseases in Bangladesh during 1987 and 2016: the changes in number and status. The list (by common name) is in alphabetic order within bold-bordered boxes.

Rice disease		Status in	
Common name	Pathogen type	1987	2016
Bacterial leaf blight	Bacteria	Major	Major
Bakanae	Fungus	Major	Major
Blast	Fungus	Major	Major
Brown spot	Fungus	Major	Major
Sheath blight	Fungus	Major	Major
Sheath rot	Fungus	Major	Major
Ufra	Nematode	Major	Major
Tungro	Virus	Major	Major
Bacterial leaf streak	Bacteria	Minor	Major
False smut	Fungus	Minor	Major
Seedling blight	Fungus	Minor	Major
Leaf scald	Fungus	Major	Minor
Stem rot	Fungus	Major	Minor
Aggregated sheath spot	Fungus	Not reported	Minor
Bacterial foot rot	Bacteria	Minor	Minor
Crown sheath rot	Fungus	Not reported	Minor
Damping off	Fungus	Minor	Minor
Grain red blotch	Fungus	Not reported	Minor
Grain spot	Fungus	Minor	Minor
Kalo bij (Kernel spot)	Fungus	Minor	Minor
Kernel smut	Fungus	Not reported	Minor
Leaf smut	Fungus	Minor	Minor
Minute leaf spot	Fungus	Not reported	Minor
Narrow brown leaf spot	Fungus	Minor	Minor
Root knot	Nematode	Minor	Minor
Root lesion	Nematode	Not reported	Minor
Root rot	Nematode	Not reported	Minor
Sheath blotch	Fungus	Minor	Minor
Sheath spot	Fungus	Not reported	Minor
Stack burn	Fungus	Minor	Minor
White tip	Nematode	Minor	Minor
Yellow dwarf	Mycoplasma	Minor	Minor

Status class: Major (Gold dotted box); Minor (Green box); Not reported (White box)
Source: Miah and Shahjahan, 1987; BRRI, 2016; BRRI, 2018

Table 2 presents the national average yield loss scenarios due to rice diseases gathered from different sources. It is highly regarded by the expert, that national yield loss in rice ranges from 10 to 15%, which includes diseases and insects (Miah and Shahjahan, 1987). It was Khan (1991) stated that the average yield loss due to rice diseases is 9.9% in Bangladesh. However, average losses due to diseases over the decade 1989-90 to 1998-99 was estimated as 3% in Boro, 5.9% in Aus, and 6% in Aman with an average for three seasons is 4.9%, contributed to an annual loss of 1.52 million ton per year (Islam and Catling, 2012). The authors also mentioned that those figures still to be regarded as an over estimation since farmer's perceptions were from which the data were derived strongly influenced by their worst memories of yield. A recent quick phone survey from 15 northern districts of Bangladesh with high officials of the Department of Agricultural Extension (DAE) revealed a different scenario, which accounted for less than 1% of yield loss in farmer's fields. However, this is a general annualized figure. The yield loss could go up in individual years when disease epidemics would be high. Kabir *et al*. (2020) has found similar results.

Table 2. National yield loss scenarios from rice diseases in Bangladesh.

Loss (%)	Mode of estimation	Year of reporting	Reference	Comments
10-15	Highly regarded expert opinion	1987	Miah and Shahjahan, 1987	Including insects
9.9	Survey estimation	1991	Khan, 1991	-
4.9	Survey estimation	1999	Islam and Catling, 2012	-
<1.0	Phone survey	2019	Authors	-

Yield loss under varying epidemics

Blast, bacterial leaf blight, sheath blight, and more recently false smut are the heavy epidemic rice diseases in Bangladesh. Yield loss in severe infection conditions has been estimated as 65.4% and 56.9% for blast disease in the irrigated and rainfed ecosystem (Hossain *et al*., 2017) respectively in the farmers' field (Table 3).

Table 3. Yield loss estimation from blast in the farmers' fields under various epidemics in Bangladesh.

Year of reporting	Loss (%)	Reference	Data environment
2017	65.4	Hossain *et al*., 2017	Variety specific (Jhalak hybrid variety), highest yield reduction in irrigated ecosystem
2017	56.9	Hossain *et al*., 2017	Variety specific (BRRI dhan34), highest yield reduction in rainfed ecosystem
2017	34.7	Hossain *et al*., 2017	Location-specific, Among 30 agroecological zones (AEZs), highest yield loss in AEZ 9

The yield loss from sheath rot disease was estimated as 75% under the highest disease severity (DS) scale of 9 (equivalent to >80% of the panicles still enclosed by leaf sheath) (Ms Tuhina-Khatun, unpublished data, Plant Pathology Division, BRRI) (Fig. 1). While in the low disease severity scale (DS 1, equivalent to ≤ 20% of the panicles still enclosed by leaf sheath), the yield loss was recorded as 20%. In a broad scenario, Shahjahan *et al*. (1994) recorded a yield loss of 31% when the crop was attacked at a critical stage due to sheath rot disease. For false smut disease, yield loss up to 87% was estimated when 67 smut balls were present in a panicle considered to be a severe outbreak situation (Fig. 2) (Nessa *et al*., 2015). For another important major disease, sheath blight caused 35% yield loss when the disease lesion reached about 80% of the plant height (B Nessa, unpublished data, Plant Pathology Division, BRRI) (Fig. 3).

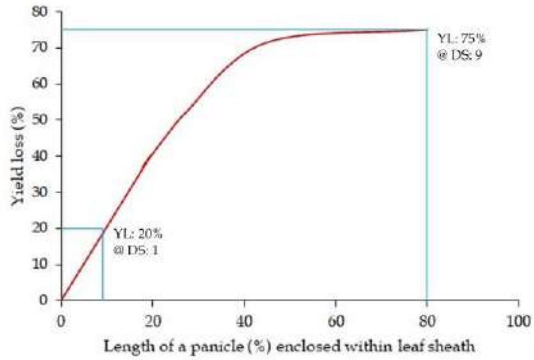

Fig. 1. Estimated yield loss from sheath rot in a severely naturally infected rice field (~ 100% incidence). DS: disease severity scale, YL: yield loss. DS 1: 0-20% of panicles still enclosed by leaf sheath; DS 3: 21-40% of panicles still enclosed by leaf sheath; DS 5: 41-60% of panicles still enclosed by leaf sheath; DS 7: 61-80% of panicles still enclosed by leaf sheath; DS 9: >80% of panicles still enclosed by leaf sheath. DS 1 represents a low disease severity scale, while DS 9 the highest disease severity scale. Unpublished data (M Tuhina-Khatun, Plant Pathology Division, BRRI).

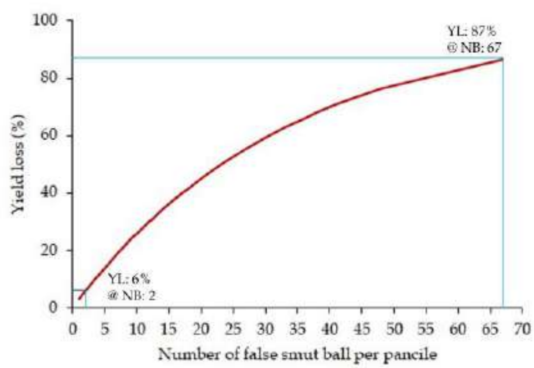

Fig. 2. Estimated yield loss from false smut infected rice fields. NB denotes the number of false smut infected balls per panicle, and YL for yield loss. Data from Nessa *et al*. (2015)

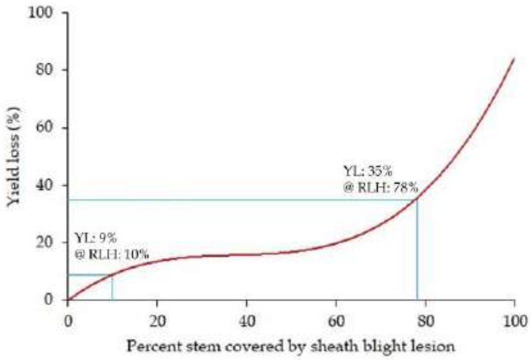

Fig. 3. Estimated yield loss from sheath blight infected rice fields. RLH denoted for relative lesion height of sheath blight disease as 0 to 100 percent. RLH 10 and RLH 78 indicate the disease symptom reached up to 10 and 78% of total plant height, respectively. YL is yield loss. Unpublished data (B Nessa, Plant Pathology Division, BRRI).

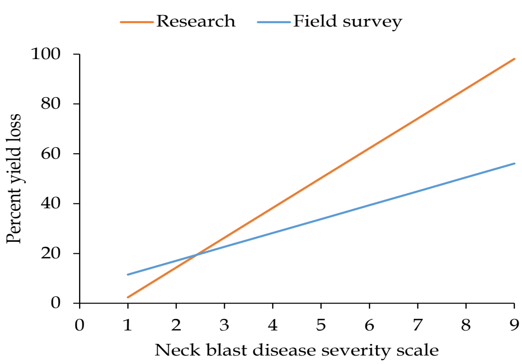

Fig. 4. Yield loss in rice due to blast disease under the whole range of disease severity scale based on research data and field survey data. The number on the x-axis, 1, indicates the lowest disease severity scale and 9 the highest disease severity scale. Odd year means the year when severe disease outbreak occurs. The research data represent the odd years when the yield loss in infected fields reached above 40%.

Yield loss under epidemic condition in odd year

It has been observed by rice scientists that a disease outbreak or epidemic generally occurred at several years intervals when favourable weather conditions prevail for a specific pathogen, and appropriate crop stages are available in the field for that organism. Currently, blast is such an epidemic disease that causes significant yield loss in farmers' fields. From research findings in farmer field under the devastating situation, blast caused the highest amount of yield loss up to 98% at disease severity scale of 9, when all the rice panicles in the field were severely affected by blast fungus (B Nessa, Plant Pathology Division, BRRI) (Fig. 4). From field survey, Hossain *et al.* (2017) recorded a yield loss of up to 56.1% due to this disease in farmers' fields from 10 agroecological zones of Bangladesh (Fig. 4).

Disease management under severe epidemics occur in odd year

The following are the potential ways to manage rice disease successfully under severe epidemics in the odd year.

A. Varietal interventions

The use of resistant or tolerant variety is the most economical and environmentally friendly method for the management of rice diseases especially for devastating diseases such as blast (Khan *et al.*, 2001; Haq *et al.*, 2002). However, the resistance is subject to break down due to the appearance of new or more virulent races of the pathogen (Ghazanfar *et al.*, 2009). Therefore, it is necessary to continually speed up the breeding program to develop resistant rice varieties for blast and other serious diseases. Plant Pathology Division of BRRI has developed some promising lines in the background of BRRI dhan28 and BRRI dhan29 to combat blast epidemics, which are in pipeline to release as varieties, which could be used in the future for cultivation in blast endemic areas.

B. Preventive measures

To control rice diseases in the farmers' field, it is economically feasible and sound to apply preventive measures rather than a curative ones. Following are some techniques which could be applied extensively to minimize disease outbreak in farmers field:

i. Use of disease free healthy seed
ii. Balanced application of phosphorus and potassium fertilizer
iii. Avoidance of excessive use of nitrogenous fertilizer
iv. Application of potash fertilizer in two splits. One split at the time of land preparation and the other at the time of last top-dress with urea fertilizer
v. Avoidance of seedbed preparation if the seedbed are disease infected in the previous year
vi. Destruction of stubbles and debris
vii. Destruction of alternate host
viii. Practice of wider spacing between two hills to avoid favourable condition for pathogen growth and development
ix. Avoid cultivation of susceptible variety
x. Following of crop rotation
xi. Seed treatment with chemicals

C. Strong forecasting system

Since disease epidemics or disease outbreaks mostly depend on weather parameters, therefore, it is urgent to develop a strong and precise weather-based disease risk forecasting system with at least one-week lead-time based on real-time weather data. The quick management option such as fungicidal treatment should also be broadcast along with weather forecasting. Digital platforms such as broadcast through TV channels, SMS to rice farmers, pronouncement through all mobile operators during phone call, and digital display of management packages at block level could be efficient and effective ways to address the disease outbreak under epidemics situation. For example: if the weather is conducive for blast disease at the booting stage, alert to be delivered to farmers through all channels recommending application of Tricyclazole/Strobin group of fungicides to rice fields in the afternoon on the susceptible varieties such as BRRI dhan28 and BRRI dhan29.

D. Effective training and advice to farmers and baseline extension agents for proper identification of rice diseases

"The farmers of rural Bangladesh, whether large or small, still depend largely on homegrown, indigenous methods-handed down from father to son to fight their unknown enemies that deplete their harvests each season" (Shahjahan, 1993). Since rice has been cultivated in Bangladesh for more than centuries and hopefully it will continue to cultivate for centuries-long then there is no alternative to provide every true farmer and Sub-Assistant Agricultural Officers (SAAOs) learning, training, knowledge, and every source of information to properly identify every type of rice disease and also manage and/or control those effectively. Initially, it will be costly and time-intense, however, in the long run, it will return enormous benefit to the country. In this context, BRRI regional stations can take a master plan to train all rice growers in their commanding areas on a long-term basis. Recently developed 'BRRI Rice Doctor' will be helpful for educated farmers to identify and manage rice diseases successfully.

E. Regularly monitoring of rice field

Monitoring and early detection would be very helpful for prevention of the rice diseases (Kim *et al*., 2017). Monitoring of rice disease progress aims to forecast and decide the time for control action as well as assess the effect of management. Therefore, it is strongly recommended and advised to the farmers and SAAOs to regularly monitor their own fields and surveillance area. For example, early detection of rice leaf blast can be managed by irrigation in the field. Likely, the appearance of Kresek (bacterial foot rot) and bacterial leaf blight (BLB) can effectively control through drainage/removing of water for few days or following alternate wetting and drying technology. Brown spot disease, therefore, could successfully be managed by balanced urea fertilization. These are the simple management practices farmers can easily adapt to their rice field by early detection of the symptoms through regular supervision and control the diseases effectively. It is now realized in both developed and developing countries that there should be a permanent program at all national levels to monitor changes in diseases outbreaks by plant pathologists, resulting from a breakdown of the inherent resistance of certain varieties, the development of pesticide resistance in the pathogens, or a shift in disease incidence due to changes in cultural practices (Shahjahan, 1993).

F. Epidemiological study

Epidemiology is defined as the study of factors that affect the spread of disease in time and space (Madden *et al*., 2007). These factors include temperature, moisture, humidity, and precipitation, etc. that influence the pathogen either positively or negatively depending on the requirement of a pathogen (Arya, 2018) to develop a particular disease. Epidemiological studies are important for the management of rice diseases as the obtained data can be processed and transformed into technologies for the management of pathogens (Arya, 2018). Such studies can be used as strategies for managing plant disease epidemics, and we can organize our plant disease control tactics under: (a) reduction of the initial inoculum/pathogen, (b) reduction of the infection rate, and (c) reduction of the duration of the epidemic, following one or more of the strategies are stated below (adopted from Arya, 2018):

i. Avoidance: Reduce the level of disease by selecting a season or a site where the amount of pathogen/inoculum is low or where the environment is unfavorable for infection, eg., right time of planting of BRRI dhan49 escapes false smut.
ii. Exclusion: Reduce the amount of initial inoculum introduced from outside sources. The infection of BLB and bacterial leaf streak (BLS) is more concentrated in hybrid. Therefore, restriction/regulation in hybrid import will reduce BLB and BLS incidence in the rice field. BRRI has already developed six hybrids that are less susceptible to BLB and BLS infection. Farmers should be encouraged to cultivate BRRI released hybrids rather than foreign hybrids, later one is more susceptible to diseases in our environment.
iii. Eradication: Reduce the production of initial inoculum by destroying or inactivating the sources of an initial pathogen such as rouging, burning of straw, destruction of alternate host, etc. These are applicable for sheath blight, sheath rot, and stem rot diseases of rice.
iv. Protection: Reduce the level of initial infection by means of a toxicant or other barrier to infection such as spraying fungicides.
v. Resistance: Use cultivars/varieties that are resistant to infection, particularly the initial infection.

The epidemiological knowledge has to reach the resource-poor farmers through farmers' groups such as farmers' field school (FFS). The FFS uses discovery-based learning methods to improve the farmers' agro-ecological knowledge, and their capacity to make decisions (Van De Fliert *et al.,* 2002). The group of farmers gathers in a weekly meeting and shares their knowledge regarding the production constraints during the rice-growing season and by team discussions, they can make decisions for practical actions in the field.

G. Location-specific, variety specific and disease-specific smart disease management packages

There are some areas that tend to more vulnerable to a specific disease. For example, Habiganj district is prone to tungro disease, the Barishal region is favourable for ufra disease, and the incidence of the brown spot is higher in Satkhira district. To manage the specific disease in this specific location, we should suggest location-specific technology. For instance, to avoid tungro in Habiganj during Aus season, we can suggest farmers cultivate a variety like BR8 because it has the highest potential to recover from tungro disease after being affected by tungro virus (Khatun *et al.,* 2017). Similarly, BRRI dhan37 has the highest potential to give better yield against tungro during T. Aman season (Khatun *et al.,* 2017). Likely, if we advocate farmers to cultivate BRRI dhan49, then we should suggest farmers to planting BRRI dhan49 with the 'recommended-sowing-window' that means within 15 June to 14 July; if the variety is sown on or before 1 July, it would most likely escape the major risk of the false smut disease and the infection rate will be less than 1% (Nessa, 2017). If the farmers are planting BRRI dhan28 and BRRI dhan29, and the favourable weather (drizzling, prolong dew in the morning, night time cool but day time hot and cloudy weather) for blast disease development prevail during booting stage, then to strongly suggest applying fungicides from the groups Tricyclazole or Strobin to save their crop from significant or severe loss.

H. Instant delivery of disease risks together with remedies

We are making progress on circulating disease management packages to the farmers through diverse ways, namely leaflet, booklet, website, mobile apps like BRRI mobile apps (RKB), krishoker Janala, etc. Through these techniques, we have already reached a section of farmers but not all. The truth is most of our farmers are not compatible with website browsers or mobile apps. We must be more digitalized to deliver our latest management technology to all rice farmers by rapid but easier techniques. Such as by sending SMS through all mobile operators to all customers and/or farmers in Bangla, so that the less educated farmers can follow it. For example, when the rice crop is in the field, and a heavy rain-storm is predicted, we can send an SMS to all farmers with the message – "Don't apply urea fertilizer in your rice field, it will increase BLB incidence".

Table 6. Sustainability, external inputs needed, and labor requirements of selected plant disease management practices of traditional farmers (most, but not all, of these practices are sustainable in the long term).

Practice	Sustainable?	External inputs	Labor
Adjusting crop density	Yes	Low	Low
Adjusting planting depth	Yes	Low	Low
Adjusting planting time	Yes	Low	Low
Altering of plant and crop architecture	Yes	Low	High
Biological control (soilborne pathogen)	Yes	High	High
Burning	Yes[a]	Low	High
Fallowing	Yes	Low	Low
Flooding	Yes	Low	High
Manipulating	Yes	Low	Low
Mulching	Yes	High	High
Multistory cropping	Yes	Low	Low
Multiple cropping	Yes	Low	High
Planting diverse crops	Yes	Low	Low
Planting in raised beds	Yes	High	High
Rotation	Yes	Low	Low
Site selection	Yes	Low	Low
Tillage	No	Low	High
Using organic amendments	Yes	High	High
Weed control	No	Low	High

[a]Under high population pressure, the slash, and burn system is neither stable nor sustainable. Source: Thurston, 1992.

I. Farmers indigenous and traditional technologies

It is important to preserve and accumulate indigenous and traditional technologies which have been practicing by rural farmers for a long. The term traditional farming is usually associated with primitive agricultural systems or preindustrial peasant agriculture that has been practiced for many generations (Thurston, 1994) in the farmers' field.

Most practices for disease management used by indigenous farmers in developing countries are cultural practices, but little information is available in an easily accessible form. Table 6 presents many of the practices of the indigenous farmers (Thurston, 1994). Today there are serious concerns about "modern agriculture", which is extremely energy-intensive, the genetic base is narrow, and stress on increasingly high yields and efficiency leads to monoculture, and sometimes to serious erosion, pollution, and excessive pesticide residues (Thurston, 1994). A historical perspective on the practices and genetic materials used by traditional farmers through the centuries may help us to develop truly sustainable agriculture. To reduce reliance on pesticides, which our poor/marginal farmers are unable to afford, and to eliminate the risk of environmental pollution, attention should be given to non-chemical methods (genetic, mechanical, cultural, and biological) of control such as burning stubble/crop residues, water management, ash application, and spraying botanics (Shahjahan, 1993). These indigenous practices should be restored and practiced to provide safe food that is also one of our sustainable development goals.

J. Strengthening network between farmers and scientists

It is of utmost necessary to make bridge the gap between farmers and scientists. Here, we have proposed a simple model/diagram (the idea adopted from Rhoades and Booth, 1982) to identify the disease problem by plant pathologists from the farmers' field, to do basic research on diseases, and to do applied research on management practices (Fig. 6). Sometimes it may require interdisciplinary collaboration with an entomologist, soil scientists, and agronomist to identify genuine problems that arise from a farmer's field. After extensive researches, potential or possible solutions should go through evaluation and adaptation under researcher supervision and farmers' perception. Finally, farmers' accepted technology will go for dissemination. This is a continuous process between farmers, scientists, and extension personnel to generate sustainable technology arise directly from farmer's field on rice diseases. To achieve maximum benefit there should be a strong linkage between research, extension, and the technology users, i.e. the farmers (Shahjahan, 1994).

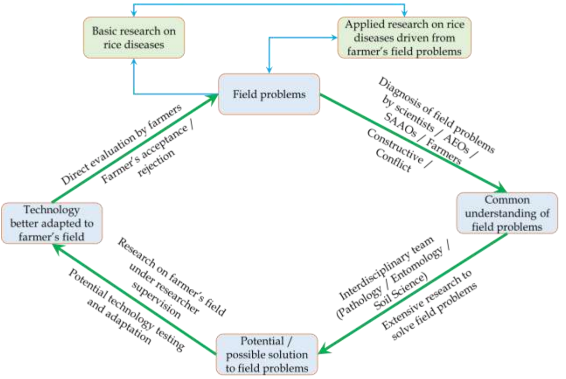

Fig. 6 Network between farmers and scientists to generate technology (Idea adapted from Rhoades and Booth, 1982).

K. Demonstrations to disseminate integrated disease management strategies to farmers field

To disseminate the latest technology, it is crucial to demonstrate it directly in the farmers' field. Whatever technologies are available or generated should reach the farmers through communication materials such as bulletins or folders; those to be written in local language and be distributed to extension agents (Shahjahan, 1993). Recent demonstrations of integrated disease management packages in farmer's field have recorded a reduction of blast disease incidence in BRRI recommendation practices over the farmers' practices by 43.57 to 70.88% (Tuhina-Khatun *et al*., 2018). The yield increase with BRRI management practices was 0.82 to 1.18 t ha^{-1} (Table 7: partial data are shown). For sheath blight disease management in Aus rice, it was observed that the disease incidence in farmers' fields in Gopalganj was reduced by 68.89% and 73.95% with trichocompost and fungicides application, respectively (Jahan, 2017). There were also advantages of yield by 0.49 to 0.69 t ha^{-1} in BRRI managed plots (Jahan, 2017). The above findings in relation to the two major disease management delivers a clear message that effective control of devastating diseases is possible in farmers' fields, which will increase the yield.

Here, we have given simple mathematics, how could we minimize our yield loss, for example, in 2020 through our existing management techniques.

Lets consider, in 2020, we have a target of clean rice production of 37.0 million tons. If we expect the maximum 1% loss due to diseases, then it will be 0.37 million tons of clean rice production loss in the whole country. We have yield advantage in our disease management plots are 0.49, 0.69, 0.82, 1.18 t ha^{-1} in different locations in farmers fields. If we consider conservative figure, we will be able to increase yield at least 0.49 t ha^{-1} through our existing management packages. And, if we assume the rice land for T. Aman 2020 as 5.0 million hectares, then the production will be increased by at least 2.45 million tons. Practically, it is not possible to receive a yield advantage from 100% rice field. If we get yield advantage from 50% or even at least 25% field, then, we have a minimum of 1.23 or 0.61 million ton of rough rice production advantage, which will be, hopefully, enough to meet the loss of 0.37 million ton of clean rice production in 2020 (assuming we will have to disseminate our rice disease management technologies through our all possible channels to the farmers' field).

Table 7. Demonstrations on rice blast disease management executed in Gazipur district of Bangladesh in Boro season, 2017-18.

Variety	Disease incidence (%)		Disease reduction (%)	Yield (t ha^{-1})		Yield increase (t ha^{-1})	Yield increase (%)
	BRRI practice	Farmer practice		BRRI practice	Farmer practice		
BRRI dhan28 (L-1)	7.75	19.61	60.48	6.22	5.90	0.32	5.42
BRRI dhan29 (L-2)	0.00	30.19	100	8.75	7.46	1.29	17.29
BRRI dhan28 (L-3)	12.00	22.22	45.99	4.99	4.43	0.66	12.64
BRRI dhan28 (L-4)	3.85	16.77	77.04	5.92	4.93	0.99	20.08
Average	5.90	22.20	70.88	6.47	5.68	0.82	13.75

Note: L-1: Kapasia-Trial 1; L-2: Kapasia-Trial 2; L-3: Shreepur-Trial 1; L-4: Shreepur-Trial 2 (Source: Tuhina-Khatun *et al*., 2018)

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

"Location, Variety, and Disease Specific Smart Management (LVDSSM)" will be the banner of the action plan for plant pathology of BRRI in the next three decades 2021-30, 2031-40, and 2041-50. Table 8 shows the salient features of the LVDSSM.

Table 8. The salient features of the action plan on 'Location, Variety and Disease Specific Smart Management' (LVDSSM) for plant pathology of BRRI in the next three decades – 2021-30, 2031-40 and 2041-50.

Programme	Phase	Stage	Action
Research & Development	Primary	III	o Identification (symptom & the disease) o Isolation (for genetic ID & propagation behavior) o Inoculation (mass inoculation technique)
		YL-EST	o Yield loss estimation (by disease severity scale)
	Intermediate	Mtg-FWK	o Management framework (considering all possible options, based on current knowledge)
		EPI	o Epidemiology (based on local conditions, not just on information from literature. Finding the exact driver(s) of the disease epidemics
	Maturation	Cali-Valid	o Calibration and Validation (testing every component of the management framework by location & variety; applying all tools)
		SmMtg	o Smart management package developed to be acceptable to farm adoption
	Follow up	CO	o Continuous observations to keep on notice if changes happening on smart management package, e.g., variety tolerance; reaction to new varieties
Dissemination	Phase-1	Train	o Training (DAE officers and lead farmers)
	Phase-2	Demo	o Demonstration (in the location of disease risk)
	Phase-3	EW	o Early warning system-based disease alert communicated to farmers

The plan consists of two broad programmes – research and development (R and D), and dissemination. The R and D will progress through four phases – (i) primary, (ii) intermediate, (iii) maturation, and (iv) follow-up. The primary phase will be completed in two stages - (i) III (identification of symptoms of the diseases and the pathogens; isolation of the pathogens for genetic identification and propagation behaviour; inoculation for disease development with the associated pathogen, and (ii) YL-EST, which is the yield loss estimation for each major disease by disease severity scale. The intermediate phase will pass through two stages - Mtg-FWK (which is the development of management framework considering all possible options, based on past and current knowledge), and EPI (i.e., epidemiology based on local conditions, not just on information from literature in order to find the exact driver(s) of the disease epidemics). The maturation phase will be completed in two stages – Cali-Valid (which is calibration and validation to undertake to test, by applying all tools, of every component of the management framework, and SmMtg (which is the development of a smart management package to be acceptable to farm adoption). The single-stage follow-up (CO) phase will be the continuous observations to keep on notice if changes happen on the smart management package, such as variety tolerance, reaction to new varieties, etc.

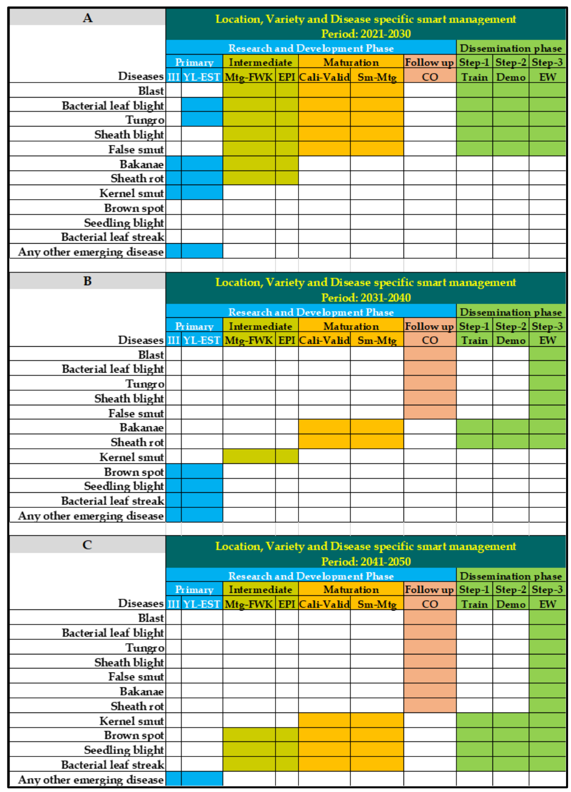

Fig. 7. The action plan on 'Location, Variety, and Disease Specific Smart Management' for plant pathology of the Bangladesh Rice Research Institute (BRRI) in the next three decades: 2021-30 (A), 2031-40 (B), and 2041-50 (C). III denotes for identification of symptom(s) and diseases, isolation for biology study and genetic identification, and inoculation for reproducing the disease; YL-EST for the yield loss estimation for major disease by disease severity scale; Mtg-FWK for development of management framework considering all possible options, based on past and current knowledge; EPI for

epidemiology based on local conditions, not just on information from literature in order to find the exact driver(s) of the disease epidemics; Cali-Valid for calibration and validation to undertake testing, by applying all tools, of every component of the management framework; SmMtg for development of smart management package to be acceptable to farm adoption; and CO for continuous observations to keep on notice if changes happen on smart management package, such as, variety tolerance, reaction to new varieties, etc.

The dissemination programme will be carried out in single-staged three phases, which includes training of officers of the Department of Agricultural Extension (DAE) and lead farmers (Trained), demonstration in the locations of specific disease risk (Demo), an early warning system-based disease alert communicated to farmers (EW).

Figure 7 shows the time dimension of the action plan for 10 major diseases in the next three decades, 2021-30, 2031-40, and 2041-50. If any diseases become a concern, they will be included in the plan. The plan has assigned varieties according to the importance and present R&D status.

CONCLUSION

The key drivers to meet food demand and sustain rice production in future are the farmers. Hence, emphasis has to be given to the farmers, and how they could reach to the existing technologies on rice disease management. However, acceptance of the technologies by the farmers depends on the authenticity of the technologies developed by the researchers. The proposed action plan accommodates both the requirements.

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AUTHORS' CONTRIBUTION

MTK, BN, MUS and MSK generated idea; BN and MUS coordinated the research; MTK and BN developed methodology; MTK, BN and MUS provided scientific insights; MTK and BN gathered data, carried out analysis and synthesis; MTK and MUS 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

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. List of identified rice diseases in Bangladesh (the list is in alphabetic order within the disease-causing organisms).

Disease	Causal organism
Fungal diseases	
1. Aggregated sheath spot	*Rhizoctonia oryzae sativae*
2. Bakanae	*Fusarium moniliforme*
3. Blast	*Pyricularia oryzae*
4. Brown spot	*Bipolaris oryzae*
5. Crown sheath rot	*Ophiobolus sp*
6. Damping off	*Achlya prolifera*
7. False smut	*Ustilaginoidea virens*
8. Grain red blotch	*Epicoccum purpurescens*
9. Grain spot	*Complex of fungi and bacteria*
10. Kernel smut	*Tilletia barclayana*
11. Leaf scald	*Microdochium oryzae*
12. Leaf smut	*Entyloma oryzae*
13. Leaf spot	*Curvularia lunata*
14. Minute leaf spot	*Nigrospora oryzae*
15. Narrow brown leaf spot	*Cercospora janseana*
16. Seedling blight	*Sclerotium rolfsii*
17. Sheath blight	*Rhizoctonia solani*
18. Sheath blotch	*Pyrenochaeta oryzae*
19. Sheath rot	*Sarocladium oryzae*
20. Sheath spot	*Rhizoctonia oryzae*
21. Stack burn	*Trichoconis padwickii*
22. Stem rot	*Sclerotium oryzae*
Bacterial disease	
1. Bacterial foot rot	*Erwinia chrysanthemi pv. chrysanthemi*
2. Bacterial leaf blight	*Xanthomonas oryzae pv. oryzae*
3. Bacterial leaf streak	*Xanthomonas oryzae pv. oryzicola*
Nematode disease	
1. Root knot	*Meloidogyne graminicola*
2. Root lesion	*Pratylenchus spp*
3. Root rot	*Hirschmaniella oryzae*
4. Ufra	*Ditylenchus angustus*
5. White tip	*Aphelenchoides besseyi*
Virus disease	
1. Tungro	*Vector: Nephotettix virescens*
Micoplasma disease	
1. Yellow dwarf	*Vector: Nephotettix virescens*

Source: BRRI, 2016

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Management and Utilization Strategy of Water Resources for Rice Production

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ABSTRACT

Declination of available water resources is threatening the dry season crop production in Bangladesh. Sustainable water management is crucial need to meet future food production. This study was aimed to determine futuristic water management strategy for rice cultivation. Both surface and groundwater is getting scarce in north-west region, whereas abundant of fresh surface water creating opportunities to irrigate dry season crops in south-central region. This study has outlined irrigation management for rice cultivation and groundwater utilization in water scarce area of north-west region. More than 75% of annual rainfall occurred during monsoon and crops other than monsoon often faced water shortage. Timely establishment of T. Aus rice on 01 May accounted average 183 mm supplemental irrigation for north-west and south-west region. Transplanting of T. Aman rice before 24 July found the low risk period of drought and gave about 1 t ha^{-1} yield advantage than late transplanting after 15 October. Supplemental irrigation in drought year gave up to 26% yield advantage than the rain-fed condition of T. Aman rice in experimental plot. Over exploitation of groundwater by famers for crop cultivation makes the groundwater status worsen. Farmers used 38% excess water than the actual requirement for Boro rice cultivation. For that annual groundwater withdrawal was higher than annual recharge causing groundwater level depletion in most of the districts. Groundwater table went below suction limit of shallow tubewell (STW) during dry season and thus it become unable to operate. Improved distribution system with plastic pipe, buried pipe could save about 25% of irrigation water. Alternate wetting and drying (AWD) irrigation method saved 20-25% water than farmer's practice. Application of these on-farm water management technologies in Boro rice reduced water demand and made the groundwater balance positive as well as reduced the groundwater withdrawal pressure. On the contrary, irrigation with less saline surface water resources in river and canals of south central regions could expand Boro production and increased land productivity. Intervention of low lift pump with plastic pipe distribution in non-saline tidal areas could increase land productivity. Besides, trapped freshwater in to the canals inside the polders and re-excavation of these canals would make crop intensification. Thus, additional food production could help to achieve sustainable development goal and sustained food security.

Key words: Supplemental irrigation, recharge, groundwater balance, less saline surface water, rice cultivation

INTRODUCTION

The sustainable use and management of freshwater resources are growing more concerns at present days for irrigated agriculture. Since water is one of the key inputs to agriculture, crop productivity largely depends on it. Bangladesh has achieved tremendous success in agriculture over the last three decades, especially in rice cultivation, and reached self-sufficiency in rice production (Mainuddin and Kirby, 2015; Timsina *et al*., 2018; Kabir *et al*., 2015). It is a densely populated country with intensive crop cultivation. About 79% of the total cultivated land in Bangladesh depends on groundwater irrigation and the remaining area is irrigated by surface water (Qureshi *et al*., 2014). The excess withdrawal of groundwater then recharged causing water table declination (BRRI, 2019). A 10 years (2007-2016) groundwater table analysis showed a declining trend in the Chapai Nawabganj district (Hasan *et al*., 2018). Consequently, the groundwater table goes below the suction limit of shallow tubewell (STW) in the Rajshahi area (BRRI, 2019). Mojid *et al*., 2019 stated a significant ($p \le 0.05$) falling

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trend of the annual maximum depths of groundwater table (GWT) in 65.71% of the monitoring wells revealed a continuous increase in groundwater abstraction in the north-west region of Bangladesh. They also reported that a significant falling trend of the annual minimum depths of GWTs in 69.71% of the monitoring wells revealed groundwater mining. Within the north-west region, Rajshahi, Pabna, Bogura, Dinajpur, and Rangpur were identified as severely depleted areas, with depletion of GWTs between 2.3 m and 11.5 m (Dey *et al*., 2013). Irrigation dependency for intensive crop cultivation with modern high-yielding varieties is one of the key factors of groundwater level depletion. Expansion of irrigated rice (Boro) cultivation causing the excess withdrawal of groundwater. Besides, excess use of water by farmers than its demand causes excess withdrawal. Hossain *et al*., 2016 reported that farmers used 20.2% excess water than required in Boro rice cultivation. They also revealed that a combination of alternate wetting and drying irrigation and a plastic pipe distribution system can save 40% irrigation than farmers management. Similar findings were also reported by Maniruzzaman *et al*., 2019. By applying AWD, farmers or pump-owners are able to save 15 to 30% of their irrigation water (Bouman *et al*., 2007).

On the contrary, a large area of the south-central region remains fallow during the dry season and has a great opportunity to crop intensification. Ibrahim *et al*., (2017) reported that Fallow-Fallow-T. Aman is the most dominant cropping pattern in the region and occupied 13.0% of the net cultivable area. Besides, water salinity remains at the permissible limit of irrigation during the dry season in most of the areas of the Barishal region (BRRI, 2019). An extensive canal network exists inside the polder of the Barishal region occupied with fresh water. Bangladesh is a densely populated country with 168 million current population and has been projected to increase to 215.4 million in 2050 (Kabir *et al*., 2015). To meet the growing demand for food, an increase in productivity of both rainfed and irrigated agriculture, specifically Boro rice cultivation is required (Mainuddin and Kirby, 2015). To feed the increasing people, there is no other option to increase food production by adapting and mitigating adverse effects on Bangladesh agriculture under changing climatic situation. Sustainable water resources management is inevitable to cope with the challenges. Besides, horizontal expansion of dry season rice in the coastal region will contribute to the national food basket. In order to sustain food security, judicious application of water will play a key role. This article specially focused on north-west, south-west and south-central hydrological region of Bangladesh with the following objectives to

- Identify suitable irrigation management practice for T. Aus and T. Aman rice cultivation;
- Develop a future action plan of safe groundwater irrigation;
- Determine the safe groundwater withdrawal in north-west hydrological region;
- Uutilize the surface water for dry season crop cultivation in the south-central region; and,
- Develop and map the action plan for three decades on reducing yield loss from water stress.

METHODOLOGY

Data collection

Historical (1987-2016) groundwater table data of the north-west hydrological region were collected from Bangladesh Water Development Board (BWDB). Thirty years of water level data of 100 observation wells were analyzed. Historical (36 years from 1981) weather data of rainfall, temperature, wind speed, humidity, and sunshine hours were collected for seven weather stations (Rangpur, Dinajpur, Ishwardi, Rajshahi, Bogura, Chuadanga, and Jashore) from Bangladesh Meteorological Department (BMD) to determine irrigation water requirement of major growing crops in the study regions. District wise area coverage of different crops was gathered from the Year Book of Agricultural Statistics (BBS, 2012 to 2018).

Irrigation requirement vs irrigation applied to crops

Hossain *et al.*, 2017 estimated irrigation water requirement and irrigation scheduling of Boro and T. Aman rice in the north-west hydrological region of Bangladesh. The CROPWAT 8.0 model (Allen, *et al.*, 1998) was used to estimate net irrigation requirements considering crop, soil, weather, and management practices. The amount of supplemental irrigation for T. Aus and T. Aman rice and net irrigation requirement of major crops in the study region was estimated using the model. Crop wise actual data on irrigation, applied by farmers in different regions were collected from Bangladesh Rice Research Institute (BRRI) and Bangladesh Agriculture Research Institute (BARI) studies.

Estimation of annual groundwater recharge

This study used the water table fluctuation method to estimated groundwater recharge (Healy and Cook, 2002). The recharge volume is given by;

$$R = \Delta H \times S_y$$

Where, R = recharge (m); ΔH = average groundwater level fluctuation (m); and, S_y = specific yield (dimension less).

Based on the laboratory test and field survey by the Institute of Water Modelling (IWM) in collaboration with BWDB, Water Resources and Planning Organization (WARPO), Barind Multipurpose Development Authority (BMDA), Department of Public Health Engineering (DPHE), they reported that the specific yield for the study area ranges between 0.08 to 0.09. Besides this, a great portion of water could be recharged from irrigated rice fields as percolation. FAO CROPWAT 8.0 model was used to determine the percolation water from the rice field in this study. The volume of recharged water has been calculated by multiplying the average depth of recharged water to the area of the district. The volume of percolation water was the product of percolation depth to Boro area coverage.

Groundwater balance study

Groundwater storage was calculated from annually recharged and withdrawal of water. Groundwater was abstracted for irrigation by all the crops and domestic uses. About 62 L water person^{-1} day^{-1} was considered in domestic use in the study region (Milton *et al.*, 2006) However, this study did not consider industrial use of water since less industrial area and was negligible water use compared to irrigation. The declination of the minimum groundwater table indicated the negative balance of groundwater and vice versa. The reduced amount of groundwater withdrawal was calculated following the trial and error method to make groundwater balance positive. This study considered the reduction of water used from the rice field by utilizing water-saving technologies during Boro rice cultivation. Groundwater balance was studied in two approaches as existing farmers' water management in Boro rice and actual irrigation requirement. The amount of irrigation applied in non-rice crops remained the same in both the approaches.

Determination of surface water salinity dynamics

BRRI has conducted a consecutive three years study from 2016 to monitor the water salinity of major river systems in the Barishal region (BRRI, 2019). Water salinity of Tentulia, Buriswar, Bishkhali, and Boleswar was measured at fixed points during the dry season (December to May). Finally, a point of each river was selected where water salinity remains < 1 dS m^{-1}. The surface water resources from the point to upstream were considered as suitable for irrigation. BRRI has assessed the amount of freshwater available for irrigation inside the polder 43/1 at Amtali, Barguna (Maniruzzaman *et al.*, 2019). The volume of water stored in the canals was calculated by taking the length, width, and depth of canals. The possible area under crop cultivation was calculated from stored water and seasonal water requirement of dry season crops.

RESULTS AND DISCUSSION

Yield loss scenarios from water stress

Uneven distribution of rainfall during the monsoon often causes water shortage and T. Aman rice faces terminal drought from this. Since the rice plant is sensitive to water stress in its reproductive phase, yield loss occurs in most areas of Bangladesh. Roy *et al.*, 2010 estimated about 13% yield loss in the experimental plot due to water stress in the reproductive phase of BR11 in the T. Aman rice season in Kushtia district. Up to 21% yield reduction of BRRI dhan49 was reported in rainfed T. Aman rice in BRRI farm, Gazipur (BRRI, 2018). Besides, rainfall shortage during July to August often delayed the transplanting of T. Aman rice resulting in increased seedling age and consequently facing yield loss. The same scenarios happen in T. Aus rice where farmers are unwilling to apply supplemental irrigation for timely crop establishment. BRRI study estimated about 25-30% yield loss due to water stress in the early period of T. Aus rice in the experimental plot. Timely pump operation by the pump owner is one of the major threats for transplanting recommended aged seedlings. Delay transplanting with aged seedling reduces the yield of Boro rice. Considering all the issues about 0.5% annualized yield loss has been estimated due to water stress (Kabir *et al.*, 2020)

Rainfall variability

Rainfall distribution of north-west and south-west regions was analyzed (Fig. 1). The annual normal rainfall of the seven stations varied from 1467 to 2290 mm. The highest (2290 mm) rainfall was observed in Rangpur followed by 1990 mm in Dinajpur and 1750 mm in Bogura. In all stations, more than 75% of rainfall occurred during the monsoon (June to October). Crops other than monsoon often face drought and irrigation needs to apply for obtaining the desired yield.

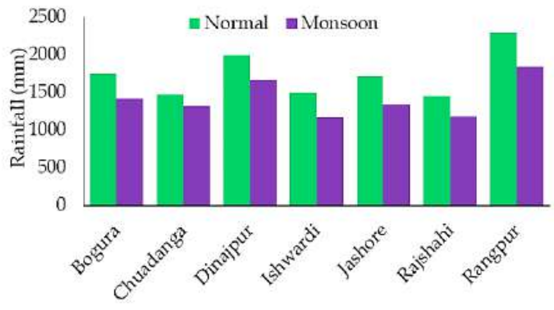

Fig. 1. Normal annual and monsoon rainfall (1981-2017) in key points of the study locations in Bangladesh.

Water management for Aus rice production

Average rainfall during May varied from 120 to 277 mm in the study locations (Fig. 2). However, 200-250 mm water is required in land preparation for T. Aus rice cultivation. Thus, supplemental irrigation needed to apply for timely land preparation. Besides uneven distribution of rainfall often causes early drought of T. Aus rice in many regions.

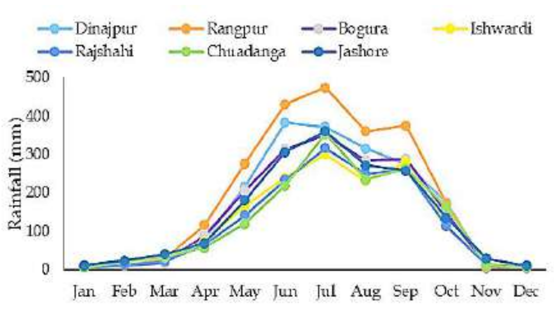

Fig. 2. Distribution of monthly normal rainfall in selected locations in Bangladesh.

CROPWAT model estimated an average of 183 mm (3 nos), 129 mm (2 nos), and 75 mm (1 no) supplemental irrigations for T. Aus rice when it was transplanted on 1 May, 10 May, and 20 May respectively (Table 1). For 1 May transplanting, the highest 262 mm irrigation was accounted in Chuadanga whereas the lowest 60 mm in Rangpur. Similarly, for 10 May transplanting, 198 mm irrigation was estimated for Jashore and 60 mm in Dinajpur, Rangpur, and Bogura region. Supplemental irrigation was not required in Dinajpur, Rangpur, and Bogura region when it was transplanted on 20 May. However, the highest 132 mm irrigation was required in Ishwardi and Jashore region.

Terminal drought mitigation for T. Aman rice cultivation

Studies (BRRI, 2016) showed that T. Aman rice often faced terminal drought due to uneven distribution of rainfall in the north-west and south-west region of Bangladesh. BRRI (2016) showed that long-duration varieties faced more drought than short-duration varieties. They also reported that delay transplanting of both short duration and long duration varieties of T. Aman rice after 24 July experienced more drought and yield loss occurred. Timely establishment of T. Aman rice before 24 July has yield advantage of about 1 t ha^{-1} than late transplanting after 15 August in rainfed condition.

A consecutive five-years study from 2010 to 2015 in the Kushtia region concluded that before 17 July transplanting is the low-risk period, 17-31 July is the medium risk and after 31 July transplanting is the high-risk period of drought for T. Aman rice cultivation. Hossain *et al.*, (2017) also reported that the 15 July transplanting of T. Aman rice in the north-west region required no supplemental irrigation, whereas 279 mm (3 nos.) irrigation was needed for delay transplanting at 15 August. Application of supplemental irrigation was found effective drought mitigation options for T. Aman rice cultivation. About 26% yield advantage was obtained by applying supplemental irrigation than rainfed condition (BRRI, 2017).

Present status of groundwater resources of north-west Bangladesh

Intensive groundwater irrigation has been practicing in the northern part of Bangladesh. As a result groundwater table is affected due to over withdrawal of water than recharge volume. Figure 3 illustrates the upazila-wise maximum groundwater level of the north-west hydrological region during 2017. It shows that among the 108 upazilas of the north-west hydrological region, the maximum groundwater level exceeds the suction limit (practically 8 m) in 44 upazilas. It means groundwater resources are getting scarce in 44 upazilas and other upazilas remain safe for STW (shallow tubewell) operation. Except Rangpur regions, the minimum groundwater level is increasing both in Pabna and Bogura region indicated that recharge amount decreased than withdrawal. In Rangpur, the historical minimum groundwater level remained almost the same means sufficient recharge happened except a few years (Fig. 4).

Table 1. Requirement of supplemental irrigation for T. Aus rice for different transplanting dates in the study locations of Bangladesh.

Location	No. of irrigation			Amount of irrigation (mm)		
	1 May	10 May	20 May	1 May	10 May	20 May
Dinajpur	3	1	0	175	60	0
Rangpur	1	1	0	60	60	0
Bogura	2	1	0	123	60	0
Ishwardi	3	2	2	203	136	132
Rajshahi	4	3	2	258	194	130
Chuadanga	4	3	2	262	196	129
Jashore	3	3	2	202	198	132
Average	3	2	1	183	129	75

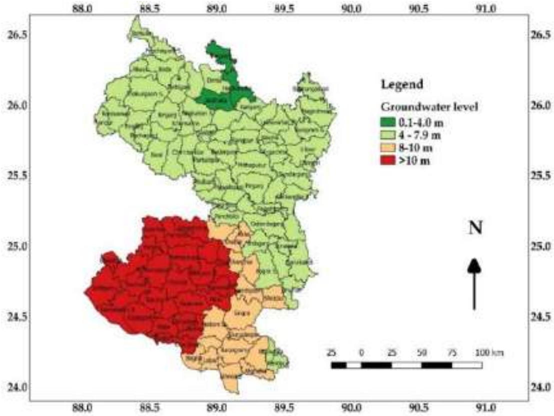

Fig. 3. Maximum groundwater level at north-west region of Bangladesh during 2017.

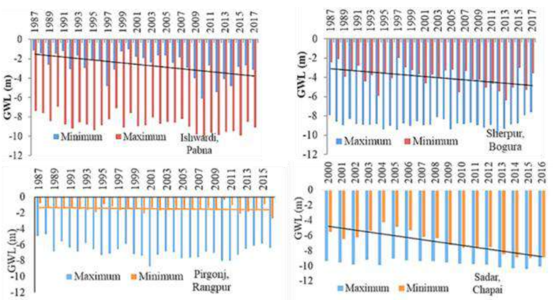

Fig. 4. Groundwater status at Pabna, Bogura, Rangpur and Chapai Nawabganj districts of Bangladesh during 1987 to 2017.

Relationship between rainfall and recharge

Generally, groundwater recharge occurs from rainfall, surface water storage bodies, river flow, irrigated rice field, etc. A close relationship was found betweenthe amount of annual rainfall and annual recharge (Fig. 5). Results showed that recharge depth is directly proportional to annual rainfall both in Pabna and Bogura districts. Figure 6 showes typical example in the Pabna district. It shows that annual rainfall at Pabna has decreased at 6 mm per year and recharge depth decreased at a rate of 2 mm per year. Although this relationship is statistically insignificant, it may be occurred due to uneven distribution and increased intensity of annual rainfall in the region.

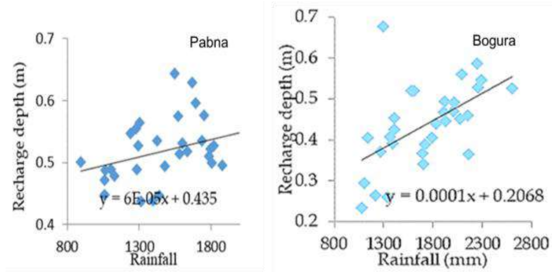

Fig. 5. Relationship between rainfall and groundwater recharge in Pabna and Bogura district of Bangladesh.

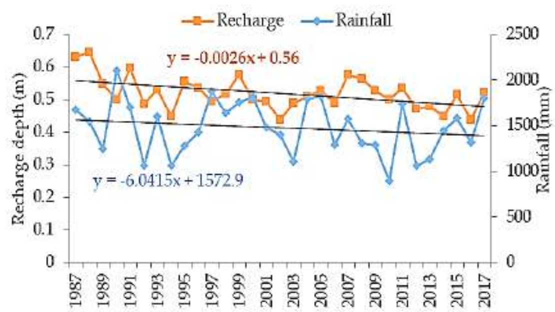

Fig. 6. Historical trend of rainfall and recharge depth at Pabna district of Bangladesh.

Irrigation requirement vs irrigation applied in major crops

Figure 7 shows the spatial distribution of irrigation water requirements of major crops. Boro rice required the maximum amount of irrigation since it is a water-loving crop and grown in fully irrigated conditions. The highest estimated irrigation requirement of Boro rice was 1056 mm at Bogura followed by 923 mm in Rajshahi and Dinajpur. The lowest irrigation requirement was 765 mm in Rangpur. Maize consumed the second-highest water next to Boro rice. The average 343 mm irrigation required for maize in the north-west hydrological region of which the highest 328 and the lowest 314 mm in Ishwardi and Rangpur, respectively. The average irrigation required for wheat, potato, mustard, and lentil was 194 mm, 163 mm, 119 mm, and 105 mm, respectively.

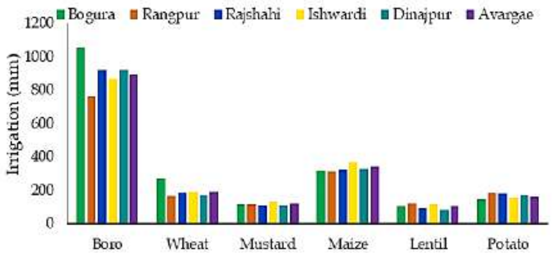

Fig. 7. Irrigation requirement of major crops in north-west region of Bangladesh.

Figure 8 shows detailed comparison of actual irrigation requirement and irrigation applied by farmers in the Boro season. Results show that farmers always use excess water than required. Farmers' practice applied an average of 38% more than the requirement in the north-west region of which the highest 50% water in Rangpur and the lowest 21% in Bogura. If farmers applied irrigation water for rice as per requirement, it would reduce the pumping cost as well as the groundwater withdrawal pressure.

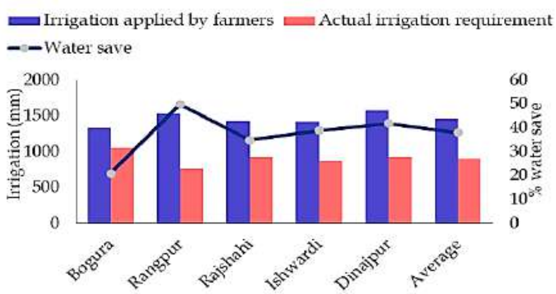

Fig. 8. Comparison of irrigation requirement and irrigation applied by farmers in different locations of north-west region of Bangladesh.

Groundwater balance in north-west hydrological region

Groundwater balance studies of Rangpur, Naogaon, Pabna, Bogura, and Joypurhat districts have been analyzed (Fig. 9). It shows that farmers are using excess water than recharged in each year from 2007 to onward. This excess withdrawal directly affected the groundwater table. But considering irrigation applied based on actual irrigation requirement the situation has been converted to positive groundwater balance. In Rangpur, on average, 0.2 billion cubic meters (BCM) per year groundwater shortage was faced since last 10 years due to over withdrawal following farmers practice. But an average of 0.55 BCM per year excess groundwater was estimated following actual irrigation requirement approaches. The same scenarios were observed in all the locations except Joypurhat where both the approaches showed negative water balance due to less recharge. Thus, either surface water utilization should be popularized or the Boro area should be reduced in order to make groundwater sustainable in the region.

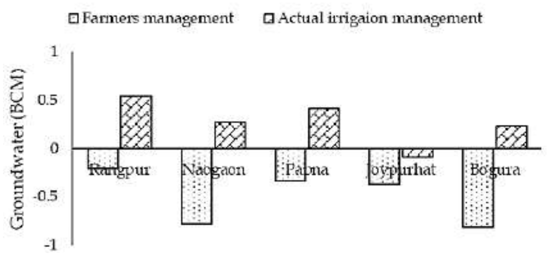

Fig. 9. Groundwater balance in farmer's management and actual irrigation requirement approaches in different districts of Bangladesh.

Since there is a good opportunity to retard groundwater table declination by less withdrawal of groundwater, the main emphasis should be given to optimizing groundwater irrigation. Irrigation to Boro rice based on its requirement should be the best option to make groundwater balance positive.

It is true that farmers are using excess water than the actual requirement all over the country. That is why proper utilization of water is a dire need especially in the water-scarce area of Bangladesh. Table 2 shows water balance for different management conditions in the study location. It was observed that at present 60% of the Boro area needed to bring under irrigation based on actual irrigation requirements in Bogura. In the Pabna district, it was 50% of the total Boro area, in Naogaon 70%, in Joypurhat 100% and Rangpur 40% area under actual irrigation requirement is enough to make groundwater balance positive.

Table 2. Groundwater balance (BCM) under different management condition in the selected study locations of Bangladesh.

Location	Boro area (ha)	Farmers' manage-ment	Boro area under actual irrigation requirement (%)						
			20	30	40	50	60	70	100
Bogura	185741	-0.85	-0.64	-0.53	-0.43	-0.33	-0.01	0.22	0.55
Pabna	63346	-0.33	-0.19	-0.12	-0.04	0.04	0.11	0.26	0.41
Rangpur	132796	-0.20	-0.11	-0.03	0.04	0.12	0.19	0.34	0.49
Naogaon	192009	-0.771	-0.61	-0.50	-0.38	-0.29	-0.18	0.08	0.24
Joypurhat	68027	-0.371	-0.31	-0.29	-0.26	-0.23	-0.20	-0.17	-0.09

Improvement of irrigation use efficiency by 2030 for sustaining Boro production

There is little scope for horizontal expansion of Boro rice cultivation in the northern part of Bangladesh. But the sustainability of Boro cultivation in the existing land is the key issue to future food security. Water security is a vital issue for rice production as well as other crop production in this region. But results showed that there is a good prospect to increase water use efficiency in the study region. Some issues need to be addressed to make Boro cultivation sustainable.

Improved water distribution system

The research finding shows that about 25% of irrigation water has been lost in the earthen canal distribution system and about 92% of that water can be saved using plastic pipe water distribution (Hossain *et al.*, 2016). Government initiatives should be taken to reduce conveyance loss of water by buried pipe water distribution systems, PVC pipe distribution, and plastic pipe distribution. Bangladesh Agricultural Development Corporation (BADC), Barind Multipurpose Development Authority (BMDA), Department of Agricultural Extension (DAE), Bangladesh Rice Research Institute (BRRI), and different NGO's should take action in this regard. Table 3 shows detailed outline of projected area coverage with improved water distribution.

Improve field water use efficiency

A huge scope exists all over the country to increase field water use efficiency. A definite irrigation scheduling based on actual irrigation requirements can improve water use efficiency. Alternate wetting and drying (AWD) irrigation method for irrigation is a technique to save irrigation of 20-25% water in this issue (Hossain *et al*, 2016). The mentioned study concluded that Intervention of AWD irrigation in 20% area of Bogura district can save 0.3 BCM water. In order to make Boro cultivation sustainable 1,11,444 ha, 3,16,73 ha, 5,31,18 ha, 9,60,08 ha and 6,80,27 ha of Boro field should bring under AWD irrigation method in Bogura, Pabna, Rangpur, Naogaon, and Joypurhat district, respectively (Table 3). A detailed action plan has been proposed in Table 5 and Table 6 describing the area to be brought under AWD irrigation with other water-saving technologies.

Table 3. Proposed plan to bring Boro area under improved distribution and actual irrigation requirement.

Location	Boro area (ha)	Boro area under improved distribution and actual irrigation requirement		
		2020	2025	2030
Bogura	185741	18574	65009	111445
Pabna	63346	6334.6	19003.8	31673
Rangpur	132796	13279.6	33199	53118
Naogaon	192009	19200.9	57602.7	96004
Joypurhat	68027	6802.7	34013.5	68027

Surface water utilization

Since groundwater resources become scarce, surface water use for irrigation should be one of the best options for sustaining agriculture. Pumping of river water for irrigation will reduce groundwater abstraction and increase recharge volume as percolation. The government should take initiative to expand 10% area of surface water irrigation by 2030.

Precision irrigation

Precision irrigation like sensor-based irrigation and model-based irrigation scheduling should be adopted to maximize irrigation efficiency. Results showed that model-based irrigation can save up to 40% more water than conventional practices.

Institutionalizing of irrigation to reduce overuse of water

Privatization of irrigation facilities caused over-extraction of groundwater by farmers. As a result, the dissemination of water-saving technologies is found difficult all over the country. Institutionalization of water resources authority could be a good option to increase water use efficiency. The government will subsidize irrigation and provide it to farmers free of cost. But a defined authority will take a decision on when to irrigate the field and how much.

Scope of Boro cultivation in south-central (Barishal) region

Less crop diversity was found in the Barishal region due to some adverse conditions like salinity, tidal water, and water stagnation. But extensive river and canal networks are the key blessings in this region. The crop sector remains underdeveloped in the coastal region although a good scope exists there. Cropping intensity values were observed 107-249% although 1,44,405 ha of land was a single cropped area (Ibrahim *et al.*, 2017). Figure 10 shows the dry season fallow land in different districts of the Barishal region.

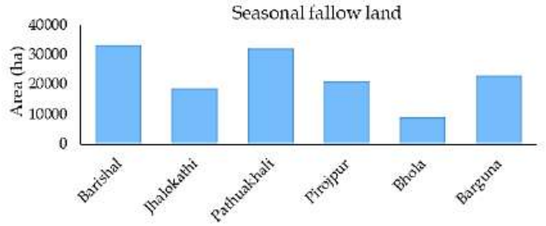

Fig. 10. Fallow land during dry season at Barishal region of Bangladesh.

Among the six districts, Barishal has the highest 33,320 ha of dry season fallow land followed by Patuakhali (32,020 ha), Barguna (23,000 ha), and Jhalokathi (18,660 ha). Cropping intensity was higher in the Bhola district and the seasonal fallow area was found 9,130 ha. Thus, the Barishal region has a good opportunity to improve cropping intensity by introducing Boro rice.

Water salinity dynamics of surface water bodies

Three consecutive years' study since 2016 on water salinity dynamics of the major river system has been summarized (Table 4). The result shows that Tentulia, Burishwar, and Bishkhali rivers are comparatively less saline than Boleswar. The maximum electrical conductivity in Tentulia river at Panpatti ghat, Golachipa was found as 0.760 dS m^{-1} (below 1 dS m^{-1}). This indicated that water from the upstream side from this point was suitable for irrigation during the dry season. Similarly, salinity remains <1 dS m^{-1} round the year at Chotobogi point in Buriswar river (0.930 dS m^{-1}), Kakchira ferry ghat point of Biskhali river (0.968 dS m^{-1}), and Charkhali ferryghat point of Boleswar river (1.080 dS m^{-1}). As a result, river and canal water above these points remained safe for irrigation. Boro cultivation in the areas below this point is also possible by introducing salt-tolerant cultivars. Diversion of freshwater from upstream to downstream part should be another option to irrigate Boro field.

Table 4. Water salinity at transition point of major rivers in Barishal region of Bangladesh.

Location	River	Maximum water salinity (dS m^{-1})		
		2016	2017	2018
Charkahli ferry ghat, Bhandaria, Pirojpur	Boleswar	0.981	0.910	1.080
Kakchira ferry ghat, Bargunasadar, Barguna	Bishkhali	0.968	0.560	0.550
Chotobogi, Taltali, Barguna	Buriswar	0.930	0.840	0.480
Panpatti, Golachipa, Patuakhali	Tentulia	-	0.550	0.760

Source: BRRI, 2019.

Water resources assessment and crop planning in polder area

The entire coastal region of Bangladesh is enclosed with 139 polders which control the movement of water inside the polder areas. A large extensive canal network exists in each polder is a good source of irrigation during the dry period. A study on water resources assessment in polder 43/1 at Amtali, Barguna showed that among the 151 km long primary, secondary and tertiary canals (>10 m width), only 11 km canals are affected by different degrees of salinity. The total stored volume of water inside the canal was 7.414503 Million m^3 in April with which about 650 ha of Boro field can be irrigated by trapping this water. Poor operation and maintenance of sluice gates, trapped canal for fish cultivation by a local leader, lack of distribution channels are the constraints to irrigation of Boro crops.

Technological intervention for Boro expansion in coastal areas

With sufficient water resources, a good opportunity exists in the Barishal region for crop intensification by introducing Boro rice during the dry season. Seventy percent area expansion in south-central (Barishal region) and 30% area in south-west saline region (Khulna) for Boro rice in fallow land by 2050 will lead to 0.75 MT additional rice in national production. Some technological interventions are needed to achieve the target in these areas. Table 5 and Table 6 showed the road map to technological intervention by 2050 for Boro rice expansion in the target locations.

Intervention of low lift pump and plastic pipe distribution system

BRRI study showed that Boro cultivation is feasible by irrigating the field from nearly canal water. Only a small intervention of low lift pump (LLP) with plastic pipe distribution system was found useful for Boro cultivation in these regions.

Burried pipe water distribution system to mitigate conveyance loss

Burried pipe water distribution system should be disseminated to convey irrigation water from the source (river, canal water) to the field. It will reduce the conveyance loss as well cost of production.

Proper operation of gate valves in the polder areas

Improper operation of gate valves is the main constraint to salinity intrusion in the polder area of Amtali, Barguna. Broken gate valves, poor gate operation, controlled by the local leader are the main issue.

Re-excavation of secondary and tertiary canals

Many secondary and tertiary canals were found to die due to siltation. These canals should be re-excavated. Besides new canals should be excavated to convey water to the tail end farmers.

Table 5. Research plan for demonstration and adoption of water management technologies.

Phase	Activity
Study and research phase	North-west and south-west (non-saline) region
	1. Site selection and characterization through baseline survey, FGDs, SWOT analysis, etc.
	2. Stakeholder engagement for adoption and demonstration trials of water-saving technologies a. Water resource availability assessment, feasibility study of free water service/water pricing on volume basis b. Timely operation of the pump, installation of new DTW/STW for community basis, operator selection c. Construction of improved distribution system
	3. Validation and adoption trials of water-saving technologies (AWD, distribution system, less irrigation required cropping pattern, surface water storage and utilization) in farmers field a. Problem identification, prioritization and scope identification for improvement b. DTW/STW selection with progressive farmers, c. Set trial at farmers' fields
	South-central and south-west (salt affected) region
	4. Site selection and characterization through baseline survey, FGDs, SWOT analysis, etc.
	5. Water resource assessment and stakeholder engagement for surface water irrigation a. Suitable water body identification, proper operation of gate valves in the polder, community engagement b. Identification and excavation of poor and dead/bad canals to improve water storage
	6. Demonstration and adoption of water management technologies in farmers field to increase Boro production a. Installation of LLP, portable solar pump and distribution system, b. Progressive farmer selection and Block demonstration c. c. Set trial at farmers' fields
	All regions
	7. Training for farmers and other stakeholders
	8. Farmers' awareness building about water-saving technologies through print and electronic media.
	9. Wide-scale demonstration in the locality and organization of field days
	10. Economic viability analysis and farmers' feedback a. Economic viability and feasibility analysis of the intervened water management technologies b. Farmers feedback
Scaling up phase	11. Extension linkage a. Workshop, field visit etc. with concerned stakeholder
	12 Upscaling a. Training for trainers b. b. Print material for sharing of information and experience

Table 6. Target for enhancing rice production through introducing water management technologies and unexplored areas across future conditions.

Cropping pattern (CP)/Intervention/ Ecosystem	Area coverage (ha)	Target intervention	Expected production increased (MT)	Time frame		
				2021-2030	2031-2040	2041-2050
North-west and south-west (non-saline)						
Targeted area coverage under recommended water management in T. Aus season	365000	255000 ha	0.008	30%	40%	30%
WST1: Supplemental irrigation for T. Aus rice	-	255000 ha	-	30%	40%	30%
WST2: Los cost/free irrigation service to the farmers	-	255000 ha	-	30%	40%	30%
WST3: Timely operation of tubewells for irrigation during T. Aus season	-	51000 nos.	-	30%	40%	30%
Targeted area coverage underwater management in T. Aman season	2540884	1500000 ha	0.30	30%	30%	40%
WST1: Supplemental irrigation in T. Aman rice for timely establishment and mitigating terminal drought	-	1500000 ha	-	30%	30%	40%
WST3: Timely operation of tubewells for irrigation during T. Aus season	-	150000 nos.	-	30%	30%	40%
Water saving technology dissemination during Boro rice cultivation	2250000	1074570	0.1	30%	30%	40%
WST1: Alternate wetting and drying irrigation method	-	1074570 ha	-	30%	30%	40%
WST2: Improved distribution system	-	86000 km	-	30%	40%	30%
WST3: Timely operation of irrigation wells	-	215000 nos.	-	30%	40%	30%
South-central and South-west (saline) region						
Targeted area coverage for Boro	140636	140636	0.75	30%	40%	30%
WST1: Installation of low lift pump and/or solar irrigation system	-	32000 nos.	-	30%	40%	30%
WST1: Improved distribution system by plastic pipe/PVC pipe/buried pipe	-	13000 km	-	30%	40%	30%
WST1: Re-excavation of existing poor and bad canals inside the polder WST2: Excavation of new canals to stored	-	20000 km	-	50%	25%	25%
Block demonstration with modern varieties by BRRI	14063	3200 nos.	-	30%	40%	30%
Training and field days		3000 nos.	-	30%	40%	30%
Targeted area coverage for Aus	416153	416153	1.20	-	-	-
Block demonstration with modern varieties by BRRI	41615	4100 nos.	-	30%	40%	30%
Training and field days	-	4000 nos.	-	30%	40%	30%

RECOMMENDATIONS

- All pumps operated by government organizations, and privately should be opened timely during us, Aman and Boro season to ensure irrigation.
- Apply supplemental irrigation in T. Aus and T. Aman rice for timely establishment and to mitigate terminal drought in low rainfall areas.

- Irrigation water pricing should be on volumetric basis.
- Distribution system should be improved by BADC, BMDA, DAE and relevant organizations.
- Massive demonstration of AWD irrigation methods should be done to popularize it.
- Institutionalization of irrigation sector is required to reduce overuse of water and provide irrigation free to farmers.
- Re-excavation of surface water bodies is needed to reserve more water to increase groundwater recharge.
- Massive block demonstration of Boro rice has to be done by using tidal water resources with the intervention of LLP.
- Freshwater harvesting is required in the canals inside the polder areas.
- Proper operation of gate valves of the polder has to be ensured.

CONCLUSION

The timely establishment of T. Aus rice needed supplemental irrigation in most of the regions. T. Aman rice transplanted before 24 July found the low-risk period of drought and gave significant yield advantage over late transplanting. Supplemental irrigation in T. Aman showed upto 26% yield increase over the rainfed condition. Maximum groundwater level exceeded the suction limit of STW in 44 upazilas out of 108 in the north-west hydrological region of Bangladesh indicated DTW should be used for groundwater irrigation. Except the Rangpur regions, the minimum groundwater level is increasing both in Pabna and Bogura region pointed out that annual withdrawal surpassed the annual recharge. This resulted from decreased annual rainfall and overused water for irrigation. Farmers applied about 38% more water than the actual irrigation requirement in the study region. The application of on-farm water management technologies can reduce excessive water withdrawal and make groundwater balance positive. Besides, huge freshwater resources in rivers and in extensive canal network inside the polder area have created opportunities to dry season crop cultivation in 144405 ha of fallow land in the Barishal region. Boro rice can be cultivated using freshwater resources in Tentulia, Bishkhali, Burishwar, and Boleswar rivers with the intervention of a low lift pump and improved distribution system.

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AUTHORS' CONTRIBUTION

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

DECLARATION OF INTERESTS

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Weather Forecast Based Rice Advisory Services in Bangladesh

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ABSTRACT

Strengthening the early warning system to forecast extreme weather and provide action-oriented advisories may increase rice yield as well as enhance the income of the farmers through minimizing risks and losses, if proper use of the generated advisory is ensured. This study assessed the importance and impact of weather forecast based advisory service (WFBAS) in Bangladesh. Literature review and field experimental data were used in a sensitivity analysis to show the impact of WFBAS on rice production. Available literatures suggested that the weather based advisory service would enhance rice yield by around 6.7-10%, but the experimental findings revealed that yield advantage could be 21.48%. Besides, the adoption of this technology would reduce the cost of cultivation by 12%, whereas the aggregate impact would increase the farmers' profit by 25%. In the sensitivity study, we considered the production and price of Aman and Boro seasons (actual and government procured prices for 2018-19) and assumed only 6.70% yield increase with 5% farmers adopting of WFBAS. As such, additional 0.172 million tons will be added to the national rough rice production and thus the nation will be benefited by 3143 million Bangladeshi taka (BDT) at the actual farmgate price and it would be 4478 million BDT at the government procured price. The return on one BDT investment in this technology would be 51-73 BDT based on actual and procured prices. The projection showed enhenced production of the rough rice at 0.119 million tons and 0.214 million tons by 2025 and 2030, on which the additional return would be BDT 2441 and BDT 5223 million at the projected actual farmgate price and BDT 3522 and BDT 6979 million at the projected Government procured price, respectively. Hence, the successful implementation of the WFBAS will help to develop resilient rice farming communities, minimize livelihood risk, reduce the cost of production, utilize resources efficienty, and enable the farmers to take maximum benefit from favorable weather conditions through improved agricultural extension services. Finally, the enhanced yield and loss reduction will help to achieve the target of Sustainable Development Goal (SDG) by 2030 through sustaining rice production in Bangladesh under changing climate.

Key words: Climate-resilience, farmers' income, future prospects, model verification, sensitivity analysis, sustainable production

INTRODUCTION

Ensuring food security is a major challenge of a country with an increasing population and reducing agricultural land as well as regular short- and long-term climate hazards (FAO, 2017a). Climate change is predicted to decrease the agricultural share of Bangladesh's Gross Domestic Product (GDP) by 3.1 percent per year (WB, 2011). Rice plays a key role in the cereal crop sector in Bangladesh by generating 90% of overall food grain production (Agriculture Diary, 2018; Rahman *et al*., 2020; Siddique *et al.,* 2020). About cent percent population of the country consume rice as their main food at 367 gm person^{-1} day^{-1} (HIES, 2016). It also has a significant (26% of total production) non-human consumption (e.g., livestock, fisheries, industries). Therefore, adequate production of rice is one of the keys

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to achieving food security. In fact, 'Rice Security' in Bangladesh is synonymous with 'Food Security', as the most other rice growing countries of the globe (Brolley, 2015).

The national agricultural policy of Bangladesh emphasizes strengthening the early warning system to forecast extreme weather events and provide action-oriented advisories to the farmers as a part of climate-resilient agricultural practices. On the other hand, we aim to enhance the integration of agricultural development and climate resilience by means of climate-smart agriculture. For this, a multi-pronged approach is required to address the full-scale climate variability and tackle the challenges arising from increasingly frequent weather and climate extremes. There is also high demand among the farming communities for such solutions (Belle, 2019). Increased climatic volatility is a huge constraint on the ability of farmers to make operational and strategic agricultural management decisions that can drastically obstruct rice production. To make the vision possible farmers need to reduce the risks from extreme weather events and address residual risks from climate variability. A recent example is the flash flood in 2017, which caused substantial damage to the production of Boro rice in the north-eastern region of the country, leading to shock in the market and rice imports (2,259 million tons) became the highest in a decade (FAO, 2017b). The weather forecast-based advisory service (WFBAS) has the potentiality to contribute to food security in Bangladesh by generating advisories and awareness of climate change. Whereas, WFBAS is the potential for reducing poverty by enhancing the rice yield and income of the farmers through reducing insect and disease outbreaks, ensuring optimum water use for irrigation, labor, and energy utilization, reduce losses and risks, reduce environmental pollution with thoughtful use of agricultural chemicals through proper management in time and also guides for the selection of the best-suited rice varieties according to the predicted climatic circumstances. This is how the system reduces the overall costs of production and increases the income of the farmers. The adoption of this technology by the agricultural extension services would contribute to achieving the sustainable development goals through enhancing productivity and return of the small-scale food producers.

Weather and its importance in rice management

The weather has an impact on rice plant's growth and development in all phases. Its volatility during the crop season, such as delay in monsoon onset, heavy rainfall, floods, droughts, severe temperatures may affect crop growth and production and eventually affect product quality and quantity (Hollinger and Angel, 2009). On the other hand, expected climate change combined with other drivers of change is likely to induce the current challenges of agricultural management (Mechiche-Alami and Abdi, 2020). For improving the food security of the country, there lies a residual risk of climate variability. Smaller-scale farmers are less capable of improving productivity under near-normal conditions; they are relatively unable to manage extreme weather incidents. In the absence of knowledge on changing climate (plant-soil-environment relationship), the farmers are highly dependent on the traditional farming understanding, which reduces farm productivity and increases farming problems such as soil salinity, over use of water, fertilizers, pesticides, etc (Nelson *et al*., 2019).

Weather-based advisory service and traditional management system

Weather forecasts for agriculture provide the necessary meteorological information to direct the farmers in making real-time special decisions for farm operations. The effects of anomalies of a weather element on a given crop are both at the cropping stage and location-specific (Das *et al*., 2010). So, WFBAS refers to manage the crop by generating growth stage-wise and location-specific agro advisory services based on weather forecasts. While in traditional management practice, the crop is being managed without meteorological information as well as crop-weather interaction.

Generally, agro advisories are issued in respect of weather-induced stresses, field operations, sowing/planting time, application of agricultural inputs, evaporation losses for irrigation, water management, weeding, harvest, and post-harvest operations, the prevalence of pests and diseases considering the crop-weather interaction (Frisvold and Murugesan, 2013) by a group of farm management specialists (agricultural statistician, agricultural meteorologist, plant pathologists, entomologists, agronomists, plant physiologists, soil scientists, and irrigation expert).

Rice advisory services based on the weather forecast

There are multiple and diverse sources of weather and climate-related threats in agriculture: insufficient water resources, drought, desertification, land loss, erosion, hailstorm, flooding, and much more (Rathore and Chattopadhyay, 2016). Efficient weather and climate information and advisory services will assist farmers in making decisions to strengthen management practices regarding agricultural climate risks (Nesheim *et al*., 2017). The Agromet/Agro Advisory Services (AAS) therefore plays an immense role in achieving sustainable agricultural productivity in Bangladesh.These services serve farmers' real-time needs and lead to weather forecast-based smart farming strategies and applications to increase crop production and food security. They can make a huge difference in agricultural production by providing benefits to the farmers from benevolent weather and reduce the adverse effects of malevolent weather.

An innovative approach to a specific development challenge

Several pieces of evidence link unmitigated climatic inconsistency to poor economic progress in emerging countries. Decreasing agricultural resources (e.g. land, labor, soil health, and water), and increasing climate vulnerability (e.g., drought, salinity, flood, heat, and cold wave) appears as the great challenges to keep the pace of food production in the background of increasing population in Bangladesh (Kabir *et al*., 2015; Kabir *et al*., 2020). Despite the documented impacts of extreme climate events and increasing concern for future agriculture, climate risk mitigation in many agricultural development strategies appears unaddressed. This may be because the agricultural system has increasingly treated climate as part of the environmental context but never as a resource for management options. The proposed approach promotes considering and managing the full spectrum of risks from weather extremes or climate variability. This novel approach can help rice growers in a better and more coordinated way in response to weather extremes or climate variability that exceeds their inherent coping capacity. This can significantly reduce the disaster risk of the rice farming communities, which is a major development challenge in Bangladesh.

WFBAS is an innovative solution for weather-ready climate-smart techniques for sustainable rice production in Bangladesh. This will enable farmers/decision-makers to make effective decisions on rice crop supervision for different climate conditions, well ahead of time. It will not only reduce the risk but also enable farmers to maximize the benefit from favorable weather conditions. Uptake of the system by the agricultural extension services can contribute to the overall food security of the country and achieve SDGs by enhancing the agricultural productivity and income of the food producers. Therefore, this study has been designed to (i) assess the weather forecast based rice advisory system for increasing productivity and show its importance on rice production; (ii) develop and mapping the research, development, and extension (RDE) activities for three decades on disseminating the WFBAS in the rice farming in Bangladesh.

METHODOLOGY

Weather research and forecasting (WRF) model for medium-range weather forecast

The Weather Research and Forecasting (WRF) Model is an atmospheric model designed for both research and numerical weather prediction (Power *et al*., 2017). It is being used for weather forecasts on micro-levels. For the development of the WRF model, a partnership was formed among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Air Force, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration. This model is a numerical weather prediction method of next-generation mesoscale designed to serve both the needs of atmospheric science and operational forecasting. This model allows scientists to make real-time predictions of the atmosphere based on real data (observations, analyses). By developing a broader research community, the WRF model performs operational prediction in a flexible and computationally efficient way with the advancement in physics, numeric, and data assimilation.

WRF model validation

The WRF model predictions were validated with the observed data collected from the Plant Physiology Division of BRRI. The seven days lead time approach was followed in the forecast validation. The plot, normalized root-mean-square error (NRMSE), and relative bias (relBias) were estimated for the verificationofprediction performance.The parameter $\hat{E}_i$ - E_i represents the error between the predicted and observed values for the i[th] sample.

The normalized root means squared error (NRMSE) is the root mean squared error (RMSE) divided by the mean of the observed data. The level of prediction accuracy was assessed by using RMSE, a good predictor that reflects the consistency of the model and its ability to explain the actual behavior of the system.

The NRMSE is provided in Equation 1, where E_i is the observed value, $\hat{E}_i$ is the model prediction, and n is the total number of predictions.

Equation 1: $$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(\hat{E}_i - E_i\right)^2}{n}}}{\frac{\sum_{i=1}^{n} E_i}{n}}$$

The relative bias (relBias) is the mean of the error in the predictions divided by the mean of the observed data. It indicates whether the model over estimates or under estimates the predictions.

The equation for relBias is provided in Equation 2, where E_i is the observed value, $\hat{E}_i$ is the model prediction, and n is the total number of predictions in the prediction horizon.

Equation 2: $$relBias = \frac{\frac{\sum_{i=1}^{n}\left(\hat{E}_i - E_i\right)}{n}}{\frac{\sum_{i=1}^{n} E_i}{n}}$$

Advisory generation

An expert group comprising of the scientists from Agricultural Statistics, Agricultural Economics, Entomology, Plant Pathology, Plant Physiology, Irrigation & Water Management, Soil Science, and Agronomy divisions of the Bangladesh Rice Research Institute (BRRI), responsible for conducting research, analyzing weather sensitivity of rice crop at different growth stages and preparing advisories (e.g. sowing, weeding, time of pesticides spray, irrigation scheduling, fertilizer application, etc. and overall crop management) based on weather forecasts.

Focus group discussion (FGD)

FGD's were conducted at three districts of Rajshahi and six districts of Khulna division with respective Deputy Directors (DD), Upazilla Agricultural Officers (UAO), Agricultural Extension Officers (AEO), and Sub Assistant Agriculture Officers (SAAO) of Department of Agricultural Extension (DAE) to draw the dissemination system of appropriate and demand-driven weather forecast based rice management for the farmers.

Experimental materials and methods for evaluation of weather forecast based advisory services

An experiment was conducted by the agromet lab of BRRI in Aus seasons at the locations listed in Fig. 1. The locations represent the West, Northwest, South, and central part of Bangladesh.

The Randomized Control Block (RCB) design has been used as a field experimental design with three replications. The experiment was aimed to assess the effectiveness of WFBAS regarding yield enhancement of rice varieties.

The WRF model was used from May to August 2016 for localized daily weather forecasting of minimum and maximum temperature, rainfall, and relative humidity. After that, the weather forecast based advisory bulletin was prepared once a week for a specific location. The weather forecast was done 7 days ahead to generate advisories for crop management and pest protection. That advisories were followed into the WFBAS experimental plots at four locations and other plots were managed through usual practices. The advisory bulletins were sent directly to the scientific assistant of the respective locations every Sunday/Monday during the study period. Data were collected through regular field visits and as per the datasheet. Observed weather data and the monthly normal value of different weather parameters were collected from Bangladesh Meteorological Department. BRRI dhan48 was tested under two different treatments (Treatment 1, T_1= usual practice i.e., control, and Treatment 2, T_2 = weather-based advisory service). Each experimental plot was comprised of 5m × 2m. A full dose of P, K, and S was applied at final land preparation on both T_1 and T_2. At maturity, a 5.0 m^2 area was harvested for grain yield with an adjustment of 14% moisture content. All other agronomic and pest management practices were also followed according to usual practice in T_1. However, sowing, transplanting, weeding, irrigation, fertilizer, herbicides, and pesticide application were adjusted based on the information generated from the weather forecast in the T_2 (Table 1).

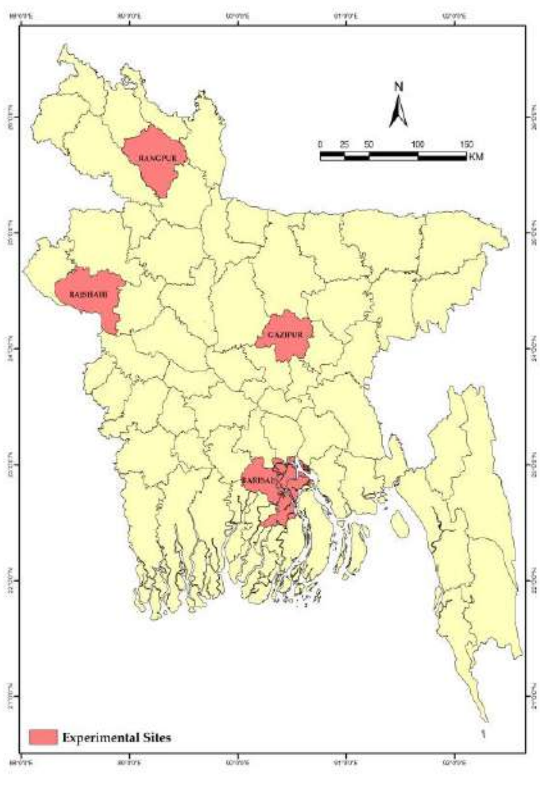


Fig. 1. Experimental locations.

Table 1. Field application of management practices.

Management	T_1: Control	T_2: WFBAS
Land preparation	Usual practice	Same as T_1
Transplanting	Usual practice	Same as T_1
Herbicide application	Applied 1 time	Did not use
Weeding	Weeded 3 times	Delayed and weeded 2 times
Fertilizer application	Applied 3 top-dress of Urea	Delayed and applied 3 top-dress of Urea
Fungicide application	Applied 2 times	Did not use
Insecticide application	Applied 3 times	Delayed and applied 2 times
Irrigation	Irrigated 9 times	Irrigated 6 times
Harvesting	Usual practice	Same date as T_1

Note: Control= usual practice; WFBAS= Weather forecast based advisory service

The supplementary irrigation was used in the T_1 plot whenever necessary, while in the case of T_2 we waited for the rainfall according to the forecast and maintained alternate wetting and drying (AWD) system. The date of the different doses of urea fertilizer 12 kg per bigha was applied based on the forecasted information on rainfall, temperature, sunshine, humidity, and the adjusted irrigation time. We did not adjust the regular planting time of the Aus season in our experiment. However, it also can be adjusted based on the forecasted rainfall information for a week. Combined analyses of variance were performed for four locations to estimate the mean yield, mean square error, and coefficient of variation.

Impact assessment through sensitivity analysis

In order to assess the impact of WFBAS with a sensitivity analysis, the study employed data from various sources. The rice production (34.44 million tons) data have been collected from the weekly crop report of DAE and converted to rough rice by considering standard conversion protocol (1 kg rough rice = 0.67 kg clean rice). Agricultural household (16.5 million) information has been generated from DAE, and rough rice procurement price for Aman and Boro (26 BDT per kg) has been taken from FPMU, 2019. The actual price of rough rice (18.25 BDT per kg) paid to the farmers has been taken from the annual review report of BRRI, 2019. The one-minute voice SMS and text SMS charges are 0.50 BDT for each by the telecom company of Bangladesh, has been considered for estimating the cost of disseminating the generated advisories. The mathematical calculation was used to evaluate the system. Besides, the return on investment (ROI) in this technology has been estimated using the following formula:

$$ROI = \frac{Net\ return\ on\ investment}{Cost\ of\ investment} \times 100\%$$

Here, the net return is the additional benefit from rice production by employing the WFBAS, and the cost of adopting this technology by the farmers is the voice SMS and text SMS charges by the telecom company of Bangladesh. It is important to mention that the required system to establish this technology is already existing in the DAE setup (e.g., FIAC). The web-based decision support system for the automatic weather forecast, advisory generation, and dissemination has been developed by the agro-meteorology and crop modeling laboratory of BRRI. Therefore, no additional fixed cost is required for disseminating this technology to the farmers.

Future prospect assessment of WFBAS

In order to show the importance of the WFBAS, we have projected the rice production, actual farmgate, and government procurement rough rice prices of Aman and

Boro seasons up to 2030. For this, we have employed Autoregressive Integrated Moving Average (ARIMA) and compound exponential growth model. The data used in the models are historical farmgate rough price from BRRI and Government procured price from Foodgrain Procurement and Monitoring Unit (FPMU), Ministry of Food. Historical rice production data has been collected from various published issues of the Bangladesh Bureau of Statistics (BBS).

RESULTS AND DISCUSSION

Experimental evaluation of weather-based advisory services

The spatial and temporal variations in significant weather parameters (e.g., temperature, humidity, rainfall, wind speed, etc.) have a major influence on farming options such as variety selection, input use, crop management, crop protection measures, harvesting, and threshing. The lack of timely and reliable weather information is a serious constraint to efficient farm planning operations. However, it may not be possible to completely avoid all farm losses due to weather parameters, but it can be minimized to some degree by implementing changes through timely and accurate weather forecast information.

Observed and projected weather condition during experimentation

In the assessment, the observed maximum and minimum temperature (^{0}C), relative humidity (%), and rainfall (mm) in experimental locations was compared with the respective predicted values generated from the WRF model. It should note that the generated output by the WRF model is on weekly basis.

The comparison of observed maximum temperatures for the season (May to August 2016) with the predicted maximum temperatures from the WRF model for the experimental locations indicated that the observed seasonal average maximum temperature was 33.18^{0}C, with a maximum of 39.50^{0}C at Rajshahi, and a minimum of 25.40^{0}C at Barishal means maximum temperature varied between 25.40 and 39.50^{0}C during May. The predicted results show that the average maximum temperature was 33.37^{0}C with a range between 25^{0}C and 41.5^{0}C, which was slightly higher than the observed. A maximum of 41.15^{0}C was predicted for Rajshahi in May and a minimum of 25^{0}C for Rangpur in August. The variation (standard error of the mean) during the season was 0.10 for both the case of observed and predicted maximum temperature. According to the average maximum temperature of a monthly basis, the temperature was higher in the month of June into the entire season for both observed and predicted cases, which were 33.74 and 34.44^{0}C, respectively, and according to the location, Rajshahi was the hottest area where average observed maximum temperature was 34.40^{0}C and average predicted maximum temperature was 34.64^{0}C (Fig. 2a). So, in the case of observed and predicted temperature, we found June as the month and Rajshahi as the location for the highest maximum temperature.

The observed seasonal average minimum temperature was 25.76^{0}C, with a maximum of 28.80^{0}C at Barishal and Gazipur, and a minimum of 18.50^{0}C at Rangpur, while the predicted average minimum temperature was 27.09^{0}C, with a range of 23.06–30.75^{0}C during May. Both, maximum and minimum of 30.75^{0}C and 23.06^{0}C were predicted for Rajshahi and Rangpur, respectively in the month of May. So, the predicted minimum temperature was found higher than the observed. The standard error of the mean during the season was calculated at 0.08 and 0.06 for the case of observed and predicted maximum temperature, respectively. According to the average minimum temperature on a monthly basis, in August and June, the highest minimum temperature was found into the entire season for observed and predicted cases with 26.63 and 27.54^{0}C, respectively (Fig. 2b). In Barishal and Rajshahi, the predicted temperature was higher than the observed temperature. The highest observed average minimum temperature was 26.16^{0}C and the highest predicted average minimum temperature was 27.75^{0}C.

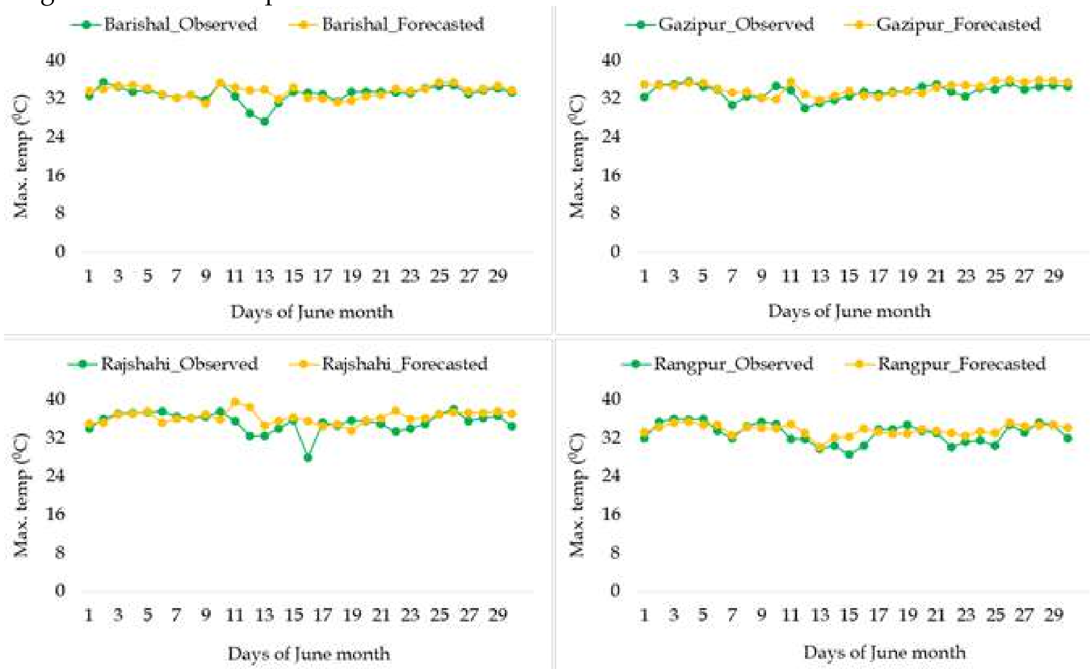


Fig. 2a. Daily observed and predicted maximum temperature (^{0}C) for June 2016 at experimental locations.

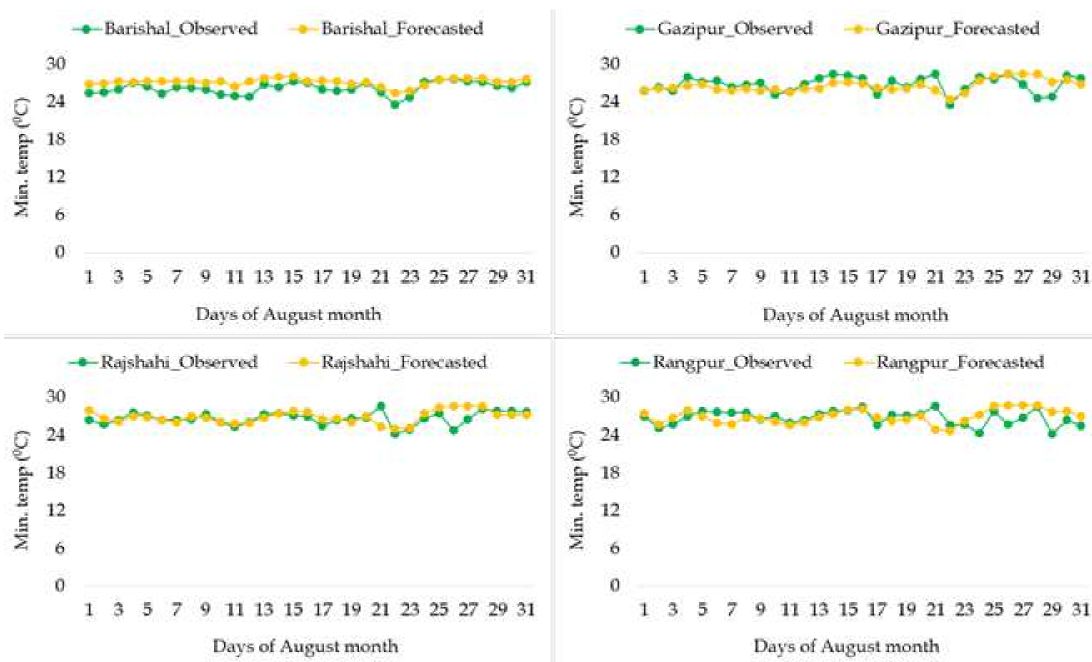


Fig. 2b. Daily observed and predicted minimum temperature (^{0}C) for August 2016 at experimental locations.

The observed seasonal average relative humidity was 82.89%, with a maximum of 100% during July-August at Gazipur, Rangpur, and Rajshahi, and a minimum of 56% during June at Rajshahi, which indicates a range of 56-100% containing a standard error of the mean 0.34. In the case of prediction, the average relative humidity was 77.74%, with a range of 43.55–100%. A maximum of 100% was projected for Rajshahi in August and a minimum of 43.55% for Rajshahi in May with a standard error of the mean as 0.42. So, the predicted relative humidity was found lower than the observed. According to the average relative humidity on a monthly basis, July was the high-humid month into the entire season for observed with 86.63%, and for prediction, it was August with 82.75% (Fig. 2c). Barishal was the high-humid area as its average relative humidity was 86.98% for observed and 81.45% for predicted.

Among all the locations, the observed average seasonal rainfall was 1323.48 mm, with a maximum total amount of rainfall was 2009 mm in July, and a minimum of 956 mm in June, while the predicted average seasonal rainfall was 1523 mm, with a maximum of 2191 mm in July, and a minimum of 1002 mm in June (Fig. 2d). In other ways, the number of total rainy days for observed and predicted rainfall during the season was 266 and 389, respectively. So, the predicted rainfall and rainy days both were higher than the observed. The average observed and predicted rainfall over the location and month was 10.76 and 12.38 mm per day with a standard error of the mean 0.98 and 0.71, respectively. If we consider the location, rainfall was highest in Barishal, and in Rajshahi, it was the lowest. The total rainfall for Barishal and Rajshahi during the season was 1827 and 865 mm for observed and 1638 and 1247 mm for predicted.

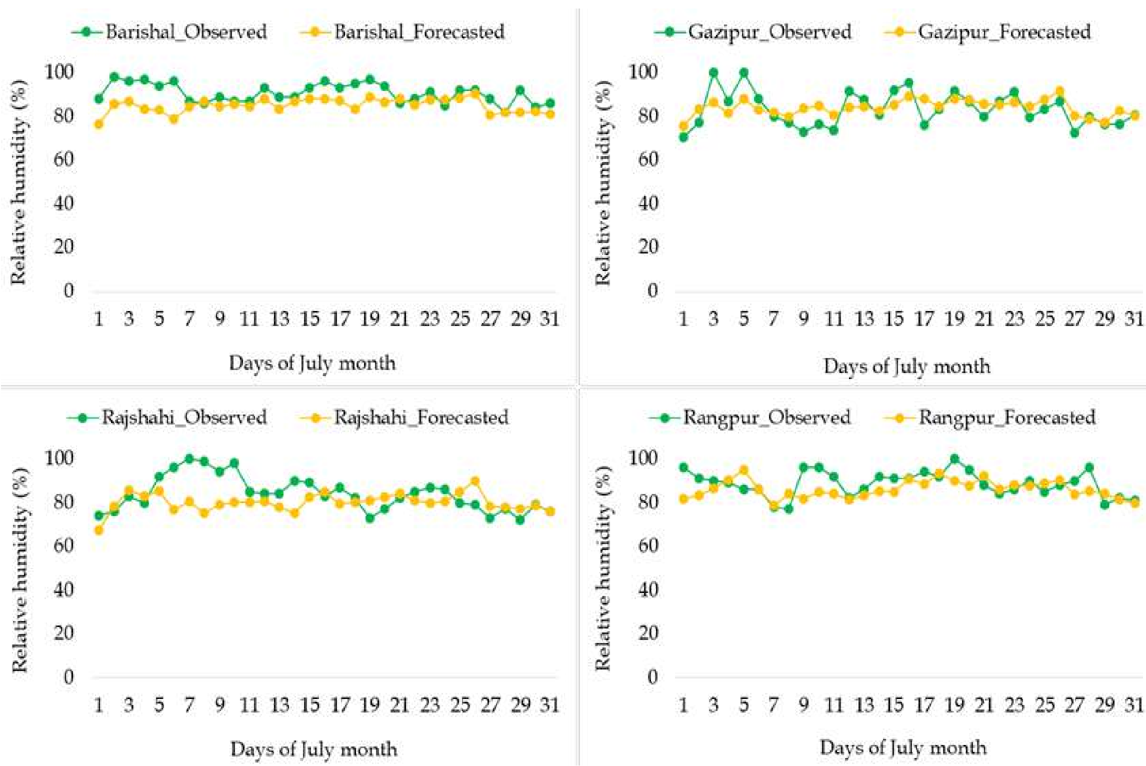


Fig. 2c. Daily observed and predicted relative humidity (%) for July 2016 at experimental locations.

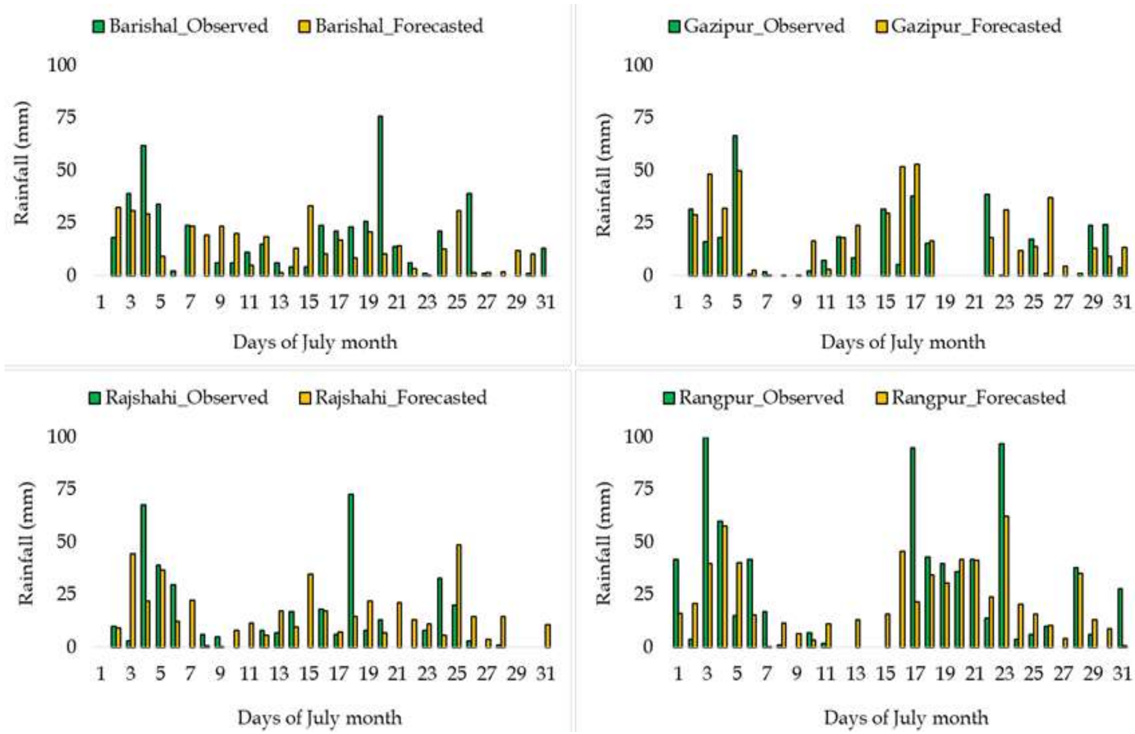


Fig. 2d. Daily observed and projected rainfall (mm) for July 2016 at experimental locations.

Observed and normal weather condition during experimentation

The average maximum temperature was higher than the normal throughout the season for all months and locations except May month at Rangpur. The average monthly observed maximum temperature was compared with normal, which varied between 0.77 and 1.34^{0}C for Barishal, 0.51, and 1.98^{0}C for Gazipur, 0.22, and 1.95^{0}C for Rajshahi, and 0.64 to 2.04^{0}C for Rangpur(Fig. 3a). The observed average minimum temperature showed a higher value compared to the normal for Barishal (varied from 0.60 to 1.02^{0}C), Rajshahi (0.36 to 0.59^{0}C), and Rangpur (0.53 to 0.88^{0}C) but the different scenario was found during the month of May at Rajshahi (0.27^{0}C) and Rangpur (1.20^{0}C). In the case of Gazipur, the difference was very minimum varied from -0.18 to 0.52^{0}C (Fig. 3b). The average relative humidity depicts almost the same as the normal throughout the season for Barishal (varied from 0.23 to 0.65%), the only exception is the month of May (-3.55%). The observed average relative humidity was found lower than normal for Gazipur and its ranges from 0.27 to 7.07%. Other than May (1.52%), Rajshahi depicts the lower observed average relative humidity than normal ranges from 2.19 to 3.70%. The situation is inverse for Rangpur compared to Rajshahi. Except for May (0.77%),other months revealed higher observed value than normal, which varied from 1.13 to 3.03% (Fig. 3c). For rainfall, May and July exceeded the normal amount of rainfall but June and August revealed less rainfall compared to normal for all the locations except during August in Barishal (Fig. 3d).

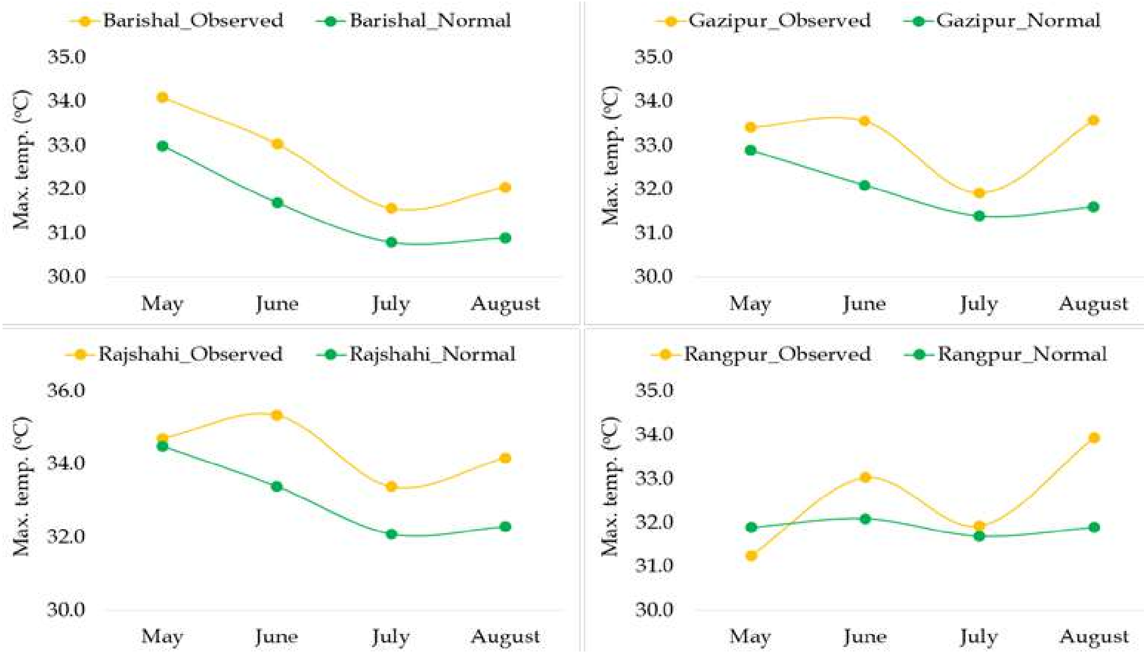


Fig. 3a. Monthly observed and normal average maximum temperature (⁰C) for the experimental locations.

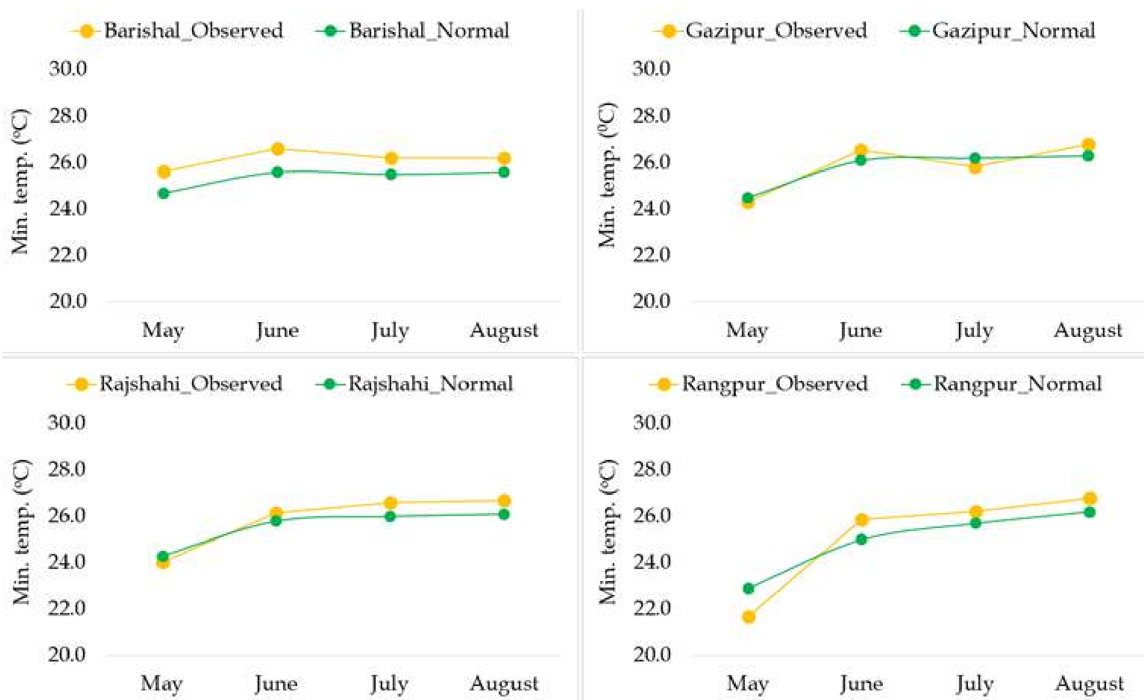


Fig. 3b. Monthly observed and normal average minimum temperature (⁰C) for the experimental locations.

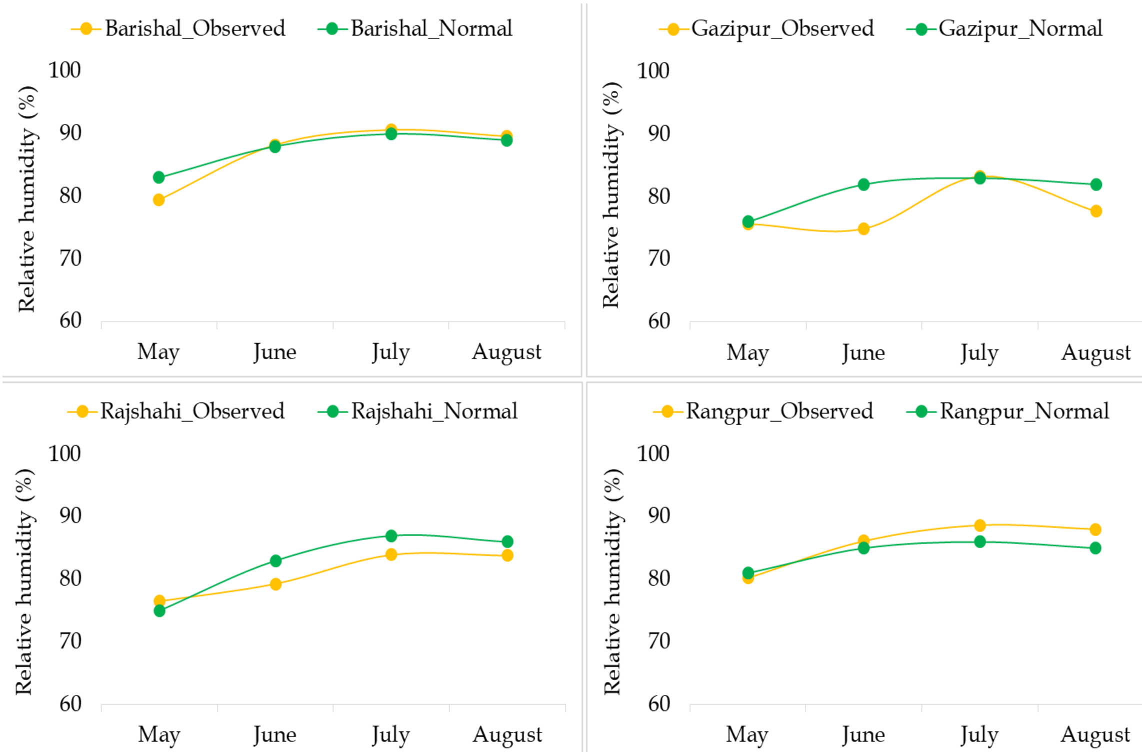


Fig. 3c. Monthly observed and normal average relative humidity (%) for the experimental locations.

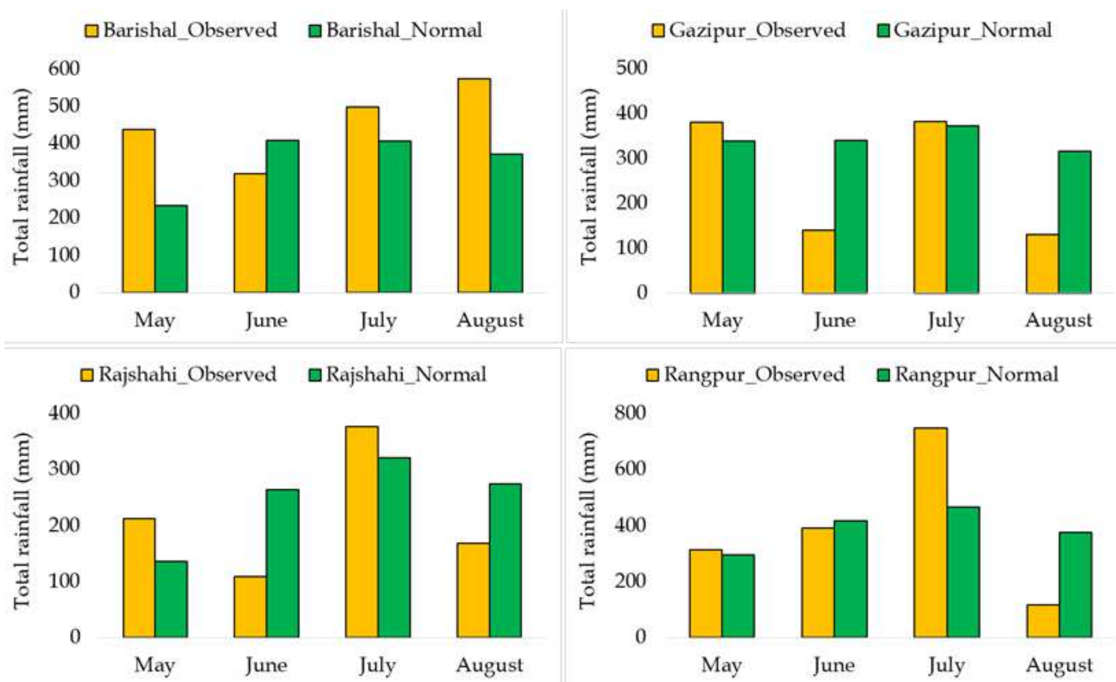


Fig. 3d. Monthly observed and normal total rainfall (mm) for the experimental locations.

Validation of WRF model predictions

Quality management is a significant requirement for the use of meteorological information. For the acceptability of the use of model performance, validation of the predicted data is essential.Fig. 4 shows the general plot of WRF model predictions and observed data for max. temp., min. temp., relative humidity, and rainfall at Gazipur, Barishal, Rangpur, and Rajshahi.

Irrespective of locations, the maximum temperature ranges from 23.5 to 41.2 ^{0}C in case of prediction and 24.5 to 39.5 ^{0}C for observed cases. Similarly, it was23.1 to 30.8^{0}C and 20.4 to 33.7 ^{0}C for predicted and observed cases, respectively in minimum temperature. The relative humidity ranges from 43.5 to 100% and 46 to 100%, and rainfall ranges from 0 to 172.1 mm and 0 to 210.6 mm, respectively for the predicted and observed data.

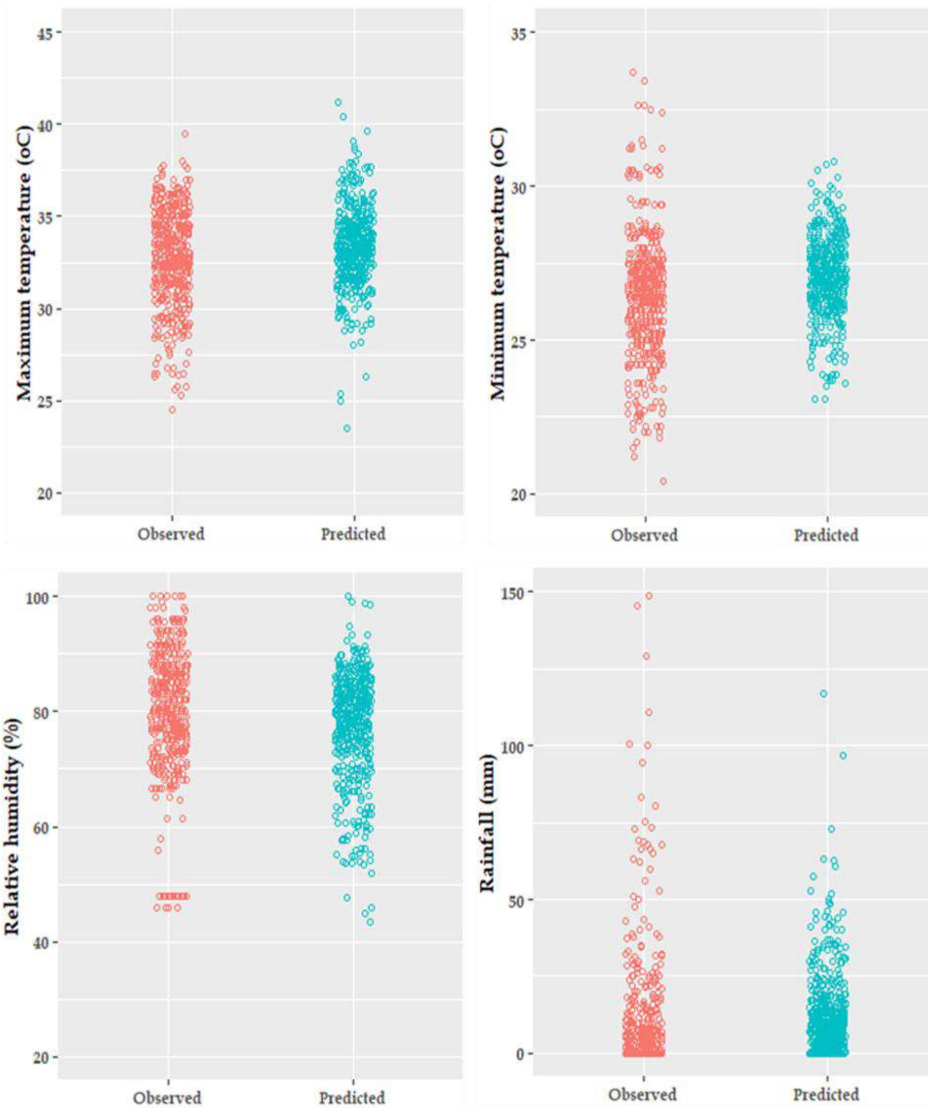


Fig. 4. Plot of WRF model predictions and observed data for four locations.

The results of NRMSE and relBias for WRF model predictions are summarized in Figs. 5 and 6. NRMSE quantifies the size of the error with respect to the mean of the observed data.

Therefore, the results show that the highest NRMSE values were shown by Rangpur for maximum temperature, and Rajshahi for minimum temperature, relative humidity, and rainfall, suggesting that errors are typically around 8.2, 11.1, 20.2, and 19.3% of the mean value for 24 hour lead time, respectively. Besides, the lowest NRMSE amongst maximum temperature, minimum temperature, relative humidity, and rainfall were exhibited by 4.6, 8, 9.4, and 6.7% at Gazipur, respectively. For 72 hour lead time, the highest NRMSE 7.4%, and 9.4% at Rangpur for max. temp., and min. temp., and 18, and 19.3% in Rajshahi for relative humidity, and rainfall. And the lowest were 4.9, 5.7, and 2.5% for maximum temperature, minimum temperature, and rainfall at Gazipur, respectively and 7.6% in relative humidity at Rangpur. In the case of 120 and 168 hours lead time, the highest values were 10.8, and 12.2% in Rangpur for max. temp., 10.2, and 10.3% in Rajshahi, and Rangpur for min. temp., 17.4, and 16.5% for relative humidity, and 21.7, and 22% for rainfall in Rajshahi, respectively. Moreover, the lowest values were 6.8, 7.2, 6.2, and 8.2% in maximum temperature, minimum temperature, relative humidity, and rainfall at Rajshahi, Gazipur, Barishal, and Rangpur, respectively. For maximum temperature, minimum temperature, relative humidity, and rainfall, were 5.2, 7.9, 8.5, and 1% at Rajshahi, Gazipur, and Barishal, respectively. The low NRMSE for max. temp., min. temp., relative humidity, and rainfall were computed in most of the locations, which signifies the capability of this model to provide an accurate prediction. Among the parameters and locations, the error lies between 1 to 20.2% which means almost 79.2 to 99% accuracy has been achieved in comparison with the observed data. Therefore, the WRF model predicted the weather parameters with low NRMSE indicating fairly good agreement with observed data. Only the location Rajshahi exhibited high NRMSE residual results for relative humidity, and rainfall.

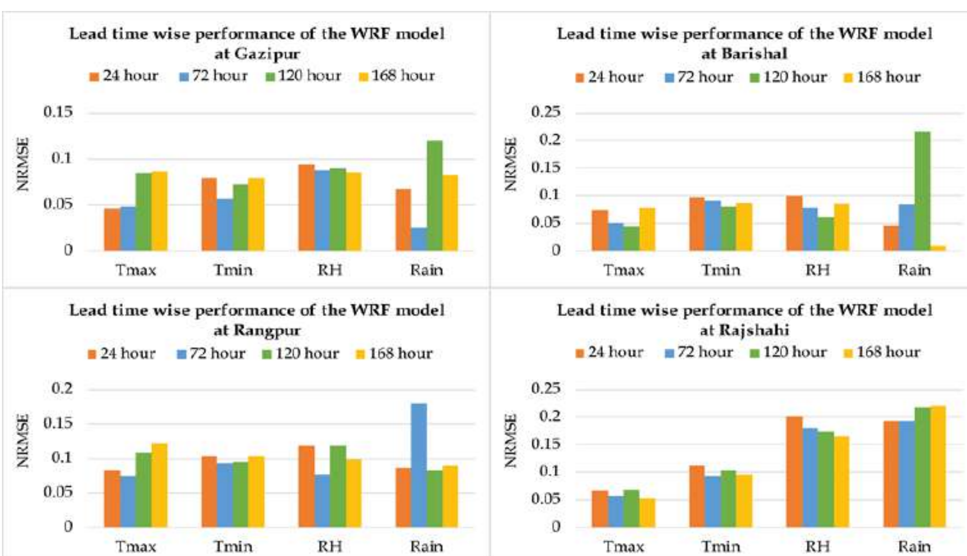


Fig. 5. Summarize the WRF model performance of max. temp., min. temp., relative humidity, and rainfall at different locations. NRMSE=Normalized root mean squared error.

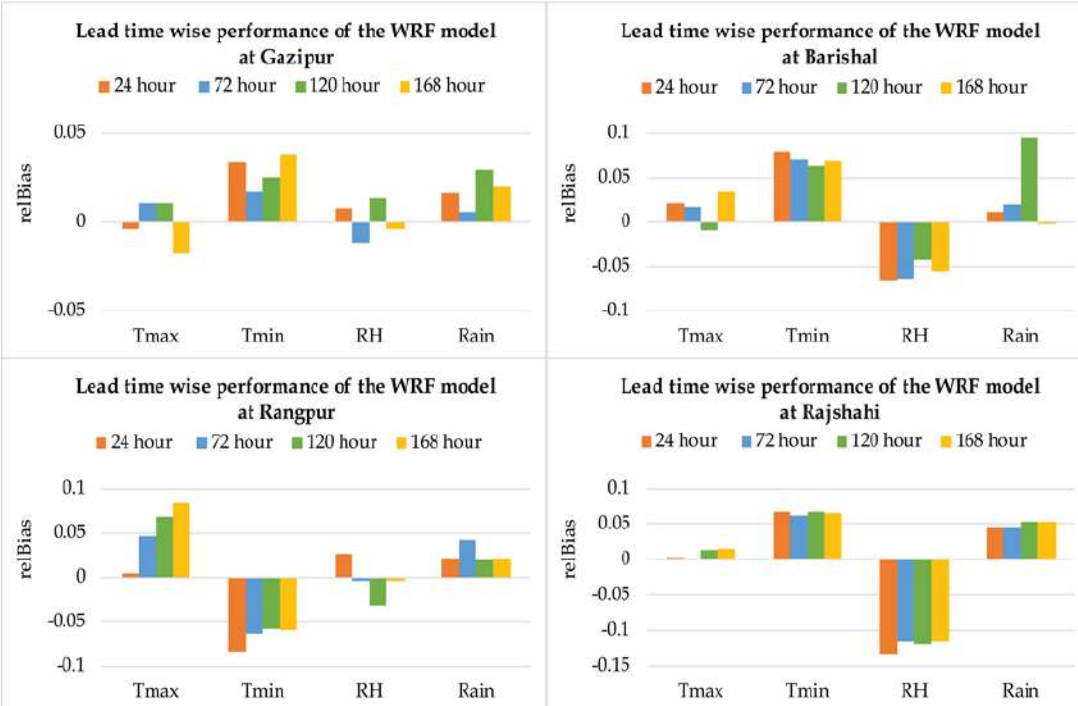


Fig. 6. Summarize the WRF model performance of max. temp., min. temp., relative humidity, and rainfall at different locations. relBias=Relative bias.

Furthermore, the relBias between the observed and predicted value using the WRF model for 24 hour lead time depicted that the max. temp. in Gazipur, min. temp. in Rangpur, and relative humidity in Barishal and Rajshahi showed underestimated (lower predictions than observed) results, which was 4%, 8.5%, 6.6%, and 13.5%, respectively.In the case of 72 hour lead time, the underestimations were 1.2% and 6.4% in Gazipur and Barishal for relative humidity, 6.3%, and 0.4% for min. temp. and relative humidity in Rangpur, and 11.5% for relative humidity in Rajshahi, respectively. For 120 hour lead time, the model shows the underestimations of 1% and 4.3% for max. temp. and relative humidity in Barishal, 5.8 and 3.1% for min. temp. and relative humidity in Rangpur, and 11.9% for relative humidity in Rajshahi. 1.8 and 0.4% underestimation accounted for max. temp. and relative humidity in Gazipur for 168 hour lead time and it was 5.5 and 0.2% for relative humidity and rainfall in Barishal, 6% and 0.5% for min. temp. and relative humidity in Rangpur, and 11.4% for relative humidity in Rajshahi, respectively. In the case of 24 hour lead time,the overestimation (higher predictions than observed) ranged from 0.3 to 2.1% for max. temp., 3.4 to 7.9% for min. temp., 0.8 to 2.6% for relative humidity, and 1.1 to 4.5% for rainfall. The ranges were 0.2 to 4.7%, 1.1 to 6.69%, and 1.5 to 8.3% for max. temp., 1.7 to 7%, 2.5 to 6.7%, and 3.8 to 6.9% for min. temp., and 0.6 to 4.5%, 2 to 9.5%, and 2 to 5.3% for rainfall in the case of 72, 120, and 168 hour lead time, respectively. Thus, relBias between the observed and predicted value showed very low overestimation and underestimation for the WRF model that signifies accurate predictions of the mentioned weather parameters. As the NRMSE and relBias values were comparatively less, the prediction model WRF is reliable. By comparing the predicted and observed values of max. temp., min. temp., relative humidity, and rainfall data using WRF model the predictions are sufficiently accurate. Therefore, the advisory generation based on the WRF model predictions of different parameters would be justified.

Advisory dissemination system

Based on the findings of the FGD, Figure 7 presents the advisory dissemination system.

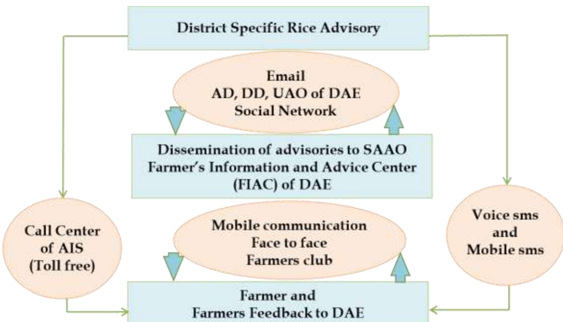


Fig. 7. Rice advisory service dissemination systems.

The generated location-specific advisories would be disseminated to the respective AD, DD, UAO, AEO, SAAO, and Farmers' Information and Advice Center (FIAC) of the DAE through email and directly to farmers by voice and text SMS. In addition, DD, UAO, SAAO's of FIAC would responsible for the dissemination of advisory bulletins to farmers in their respective areas through mobile communication, face-to-face meetings, or contact with the farmers club. The call center of Agricultural Information Service (AIS) can disseminate advisories to the farmers by voice SMS service and also inform the update if necessary. A toll-free number is essential to make the advisory service free for the farmers. Finally, farmers' feedback would also be incorporated regularly, if justifiable.

Findings from numerous literature on weather forecast based advisory services

There are some findings on the weather forecast-based advisory services and their impacts on crop management. In India, the National Center for Medium-Range Weather forecasting (NCMRWF) also evaluated the impact on various crops of weather-based agro-advisory services (Wheat, rice, millets, maize, red gram, chickpea, mustard, cumin, jute, cotton and tobacco, apricot, peach, banana, tomato, and spinach). Of the 127, 15 AAS units have been selected for impact study based on the existence of NCMRWF's effective weather-based agro-advisory service. Two AAS contact farmers villages and 2 non-AAS contact farmers villages were selected on each unit. From each village, there were designated 20 AAS contact farmers and 20 non-AAS contact farmers. Finally, data were collected from 600 AAS and 600 non-AAS farmers. The study was carried out three years comprising of 3 Kharif and 3 Rabi seasons. In the case of rice, 7 stations (Raipur; Thrissur; Kalyani; Ludhiana; Bhubaneshwar; Hyderabad, and Pantnagar) were selected. The study revealed that the impact of AAS on the cost of cultivation decreased by 5-12% and gross return, net return, and yield increased by 8-20%, 16-20%, and 8-20%, respectively. Some researchers (Maini and Lathore, 2010; Chakraborty *et al.*, 2018; Das *et al.*, 2019) have been tested weather-based management practice and termed as AAS over the traditional practice that is non-AAS in farmer's field and has found a net benefit of 6.7-15% in the overall yield of rice. Besides, they have also reported AAS to reduce 2-5% cost of cultivation, gained 19.74% in net return, and earned more profit (USD 50.0 to USD 95.0) per ha of land over the non-AAS. A further study was carried out by the National Center for Agricultural Economics and Policy Research (NCAP) to assess the economic impact of weather forecast advisories during 1996, 2009, and 2015. The study reported that due to the adoption of agromet advisory services, farmers obtained an economic benefit of 10-25 percent (Chattopadhyay, 2018). Ananta Vashisth *et al.*, (2013) and Khan *et al.*, (2018) also studied the economic impact of agro-met advisory services on different crops and noticed that farmers can reduce input costs up to 6% in wheat, 9.6% in carrot, 2.4% in maize, 1.8%-7% in rice and increase net profit by 0.9%, 3%, 14% and 4-11%, respectively.

Performance of WFBAS in field experiment

As already mentioned in the methodology, we used BRRI dhan48 in our experiment. The performance of BRRI dhan48 under WFBAS yielded better (4.75 tha^{-1}) than control (3.91 tha^{-1}). The research has demonstrated 21.48% (with a confidence interval of 4.33±1.96*0.123) higher yield for field implications with forecast-based advisory service than the control plots (Fig. 8). The rice crop thus appears sensitive to weather changes, as the percentage of the yield variability was much greater.The reasons behind the yield advantage of the WFBAS over the control could be the proper utilization of chemical fertilizer and weather forecast-based insect management. In the WFBAS plot, the fertilizer application date was adjusted with the rainfall forecast. Whereas, the control plot was affected by rainfall after fertilizer application. The forecasted weather was favorable for stem borer (SB), therefore, the WFBAS took precautionary measures to prevent SB at the vegetative phase of the rice plant. On the other hand, the control plot used insecticides only after the emergence of SB.

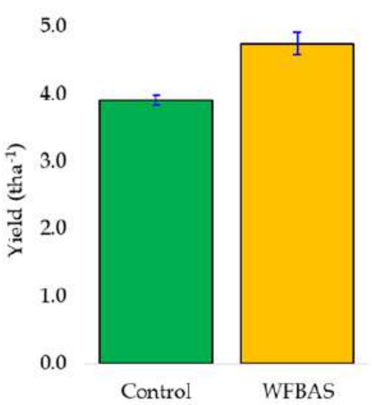


Fig. 8. Yield comparison between WFBASand traditional system.

Fig.9 showed the location-specific yield (tha^{-1}) performance of BRRI dhan48 under two different management systems. Among all locations with WFBAS, the yield of Rajshahi was the highest (5.46 tha^{-1}), followed by Gazipur (4.67 tha^{-1}), Rangpur (4.55tha^{-1}), and Barishal (4.32tha^{-1}). In the same place,the yield of Rajshahi was the highest (4.17 tha^{-1}) among the control plots, followed by Gazipur (4.03tha^{-1}), Rangpur (3.72tha^{-1}), and Barishal (3.72tha^{-1}). BRRI dhan48 with the WFBAS showed significantly better yield performance than the control one irrespective of the location, but excellent has been observed in Rajshahi (30.94%).

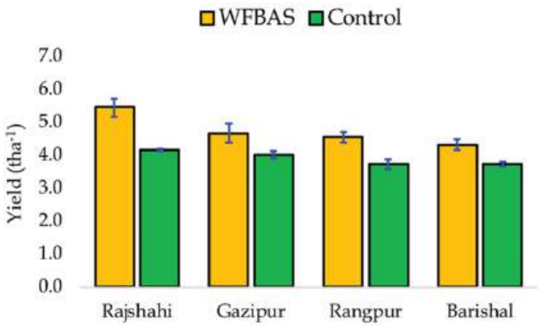


Fig. 9. Location-specific yield(tha^{-1}) performance of BRRI dhan48dueto management systems. WFBAS=Weather forecast based advisory service.

Impact assessment

Our experimental findings reveal that the yield advantage of WFBAS is 21.48% over the control. However, the reviewed numerous literature found it 6.7-15%. In order to show the minimum potentiality of this technology towards generating benefit in rice production, we considered only the minimum yield increment found in the literature. Therefore, this study used only 6.7% yield increment to show the impact of this technology on the total rough rice production in Bangladesh. Moreover, the results of the sensitivity analysis revealed that the adoption of this technology will stimulate total rough rice production by 0.034, 0.069, 0.103, 0.138, and 0.172 million tons, if only 1, 2, 3, 4, and 5% adoption rate can be ensured, respectively (Fig. 10). We have valued the farmers' additional benefit by adopting WFBAS technology in terms of actual

(18.25 BDT per kg) as well as the government declared rough rice farm-gate prices (26.00 BDT per kg) during 2018-19. The results showed that the nation will be benefited by adding 629, 1257, 1886, 2514, and 3143 million BDT, if only 1, 2, 3, 4, and 5% of farmers adopt the WFBAS, respectively. However, if the Government declared price can be ensured the benefit will be up to 896, 1791, 2687, 3582, and 4478 million BDT, respectively (Fig. 11).

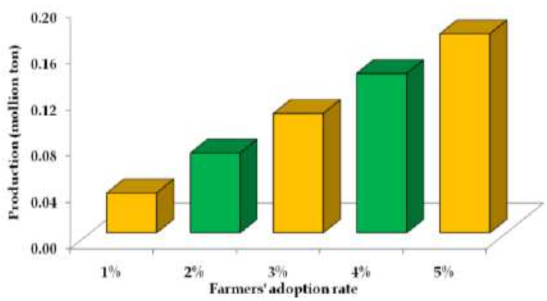


Fig. 10. Additional production through WFBAS. WFBAS=Weather forecast based advisory service.

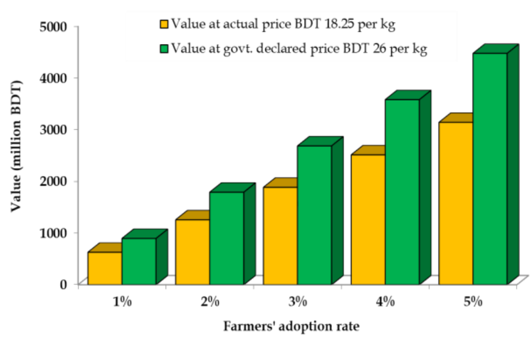


Fig. 11. Benefit from adopting WFBAS in rough rice production. WFBAS=Weather forecast based advisory service.

Therefore, increasing the adoption of this technology will certainly increase the national rice production and income of the farmers that will contribute significantly to ensure and sustain national food security. It is important to mention that the farmers' costs of production will remain the same or even can be reduced (2-5%) if this technology is adopted successfully (Chakraborty *et al.,* 2018). For implementing this technology, we recommend using the existing setup of BRRI and the DAE. Therefore, only voice and text SMS to farmers on rice advisories every 5 days interval will be required. The costs have been estimated as 12.05, 24.09, 36.14, 48.18, and 60.23 million BDT for 1, 2, 3, 4, and 5% farmers adoption, respectively. In this regard, the return on one BDT investment to this technology will be 51 BDT according to the actual price and 73 BDT if the government procured price is materialized at the farmgate level. The policies of the government should therefore go in favor of the widespread and effective dissemination of WFBAS to the end-users.

Future prospects of WFBAS

We already set a target of bringing 3% of total farmers under the WFBAS by 2025, and 5% by 2030.The forecast results showed that the rough rice production would be increased by 0.119million tons if the adoption goal of 3% is met by 2025 and that would be 0.214million tons for 5% adoption by 2030 (Fig. 12).

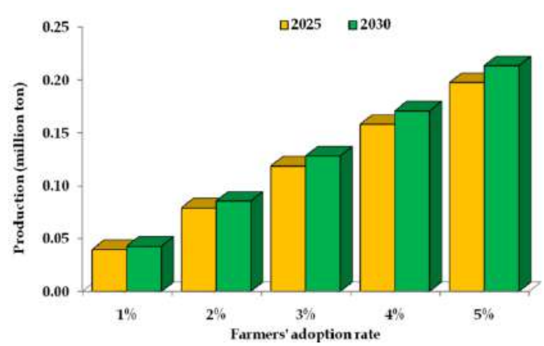


Fig. 12. Projected additional production through WFBAS. WFBAS=Weather forecast based advisory service.

Moreover, by the implementation of WFBAS, the return from the additional production would be BDT 2441 and BDT 5223 million at the rate of actually estimated rough rice prices 20.59 BDT per kg and 24.46 BDT per kg by 2025 and 2030, respectively. It will be 3522 and 6979 million BDT with the projected government procured price of 29.71 BDT per kg and 32.68 BDT per kg, respectively (Fig. 13 and 14).

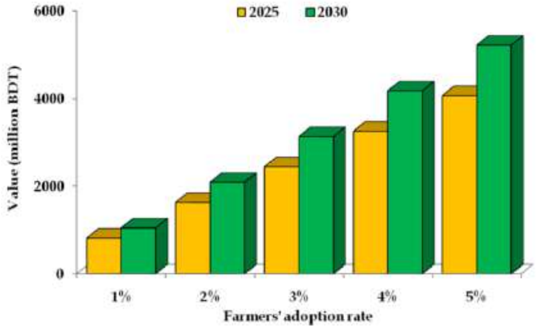


Fig. 13. Projected benefit from adopting WFBAS in rough rice production at the actual farmgate price. WFBAS=Weather forecast based advisory service.

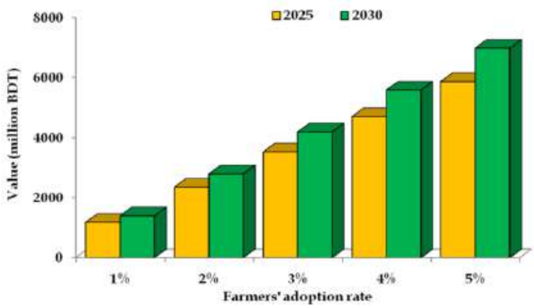


Fig. 14. Projected benefit from adopting WFBAS in rough rice production at the government procured price. WFBAS=Weather forecast based advisory service.

The estimated return according to the above projections will be 67 and 96 BDT from investing one BDT in this technology with the actual and government procurement prices by 2025, respectively, and that will be 86 BDT and 115 BDT by 2030 (Fig. 15). Therefore, the

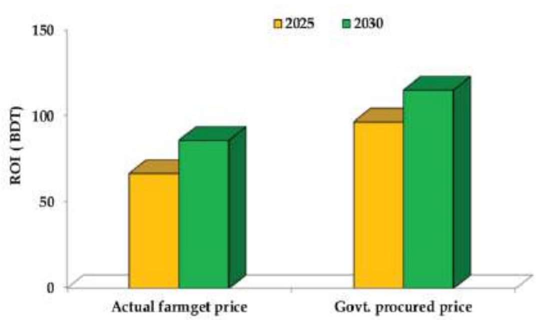


Fig. 15. Projected rate on investment from adopting WFBAS in rough rice production at the actual farmget and government procurement prices. ROI=Return on investment, WFBAS=Weather forecast based advisory service.

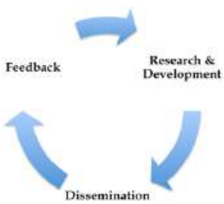
investment in the dissemination of the WFBAS in the smart farming process will be much beneficial for sustainable rice production and increasing farmers' income.

Research, development and extension (RDE) for three decades on enhancing rice production

The RDE activities of developing weather forecast-based rice advisory services in Bangladesh have been drawn based on the three core pillars. These are- research & development, dissemination, and feedback. These interlinkage pillars will work cyclically. Table 2 presents the decade-wise actionable programmes from the period 2021 to 2050 to establish the weather forecast-based rice advisory services. By 2030 we will develop the web-based decision support system (DSS) and identify the threshold level of the weather parameters responsible for insects and disease in different stages of rice crop. Our target is to bring 5% of rice farmers of the country under the advisory services in this decade and 50% in 2050. The developed database during 2021-2030 will be used to improve the DSS to make the advisory system automated during 2031-2040 and it will continue to upgrade based on the generated data from the experiment and field survey. The identification of threshold level of weather parameters responsible for insect and disease in different stages of rice crop will be continued. However, the feedback from the farmers, extension officials, and scientists/experts on the weather forecast-based rice advisory system and services will be incorporated in improving the DSS during 2041-2050 and beyond. Whereas, Table 3 presents the programme-specific activities (action plans) to materialize the ultimate goal of this study.

Table 2. Decade wise actionable programmes.

Theme: Weather Forecast Based Rice Advisory Services

Pillar		Programmes		
		Period		
		2021-2030	2031-2040	2041-2050
	Research and development	• Development of web-based decision support system (DSS) • Identification of the threshold level of the weather parameters responsible for insect and disease in different stages of rice crop	• Improving the DSS to make the advisory system automated • Continuing the identification of threshold level of weather parameters responsible for insect and disease in different stages of rice crop	• Continuation of the improvement of DSS • Continuation of the identification of threshold level
	Dissemination	• 5% rice farmers will be brought under the advisory services	• Total 25% rice farmers will be brought under the advisory services	• Total 50% rice farmers will be brought under the advisory services
	Feedback	• The adopted farmers and extension officials will provide their opinions about the service and advisories	• The adopted farmers and extension officials will provide their opinions about the service and advisories	• The adopted farmers and extension officials will provide their opinions about the service and advisories

RECOMMENDATIONS

- To enhance the productivity and profit from rice yield, a massive and efficient program for wider demonstration, refinement, and dissemination of weather forecast-based advisory service in an integrated way across the country should be taken.
- An automated decision support system should be established to transfer the advisory services from the origin to the end-users in the best and effective way.
- To make the system successful, we need to strengthen the capacity of BRRI, DAE, and develop the personnel accordingly through national and international expert linkage/training.
- A strong collaboration is required among the BRRI, Bangladesh Meteorological Department (BMD), Bangladesh Water Development Board (BWDB), DAE, and end-users.
- As the farmers are the end-users of this technology, they should be well trained in Weather Forecast Based Advisory Service (WFBAS) system.
- The government should ensure quick and adequate supports regarding the popularization, adoption, and proper use of WFBAS.
- We place a target here to bring only 5% of total farmers under this technology by 2030, which will contribute significantly as one of the vital factors for achieving the SDG target 2.3: doubling the agricultural productivity under goal 2: zero hunger.
- The results of this study will provide suitable guidelines to the policymakers towards formulating policy decisions on implementing WFBAS.

Table 3.The program-specific research, development, and extension activities.

Program	Action	2021-2030		2031-2040		2041-2050	
		2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Development of web-based decision support system (DSS)	• Development of user interface of web-based decision support system to generate weather forecast based advisories						
	• Establish collaboration with the Bangladesh Meteorological Department						
	• Medium range weather forecasting system development using Numerical Weather Prediction (NWP) model						
	• Model validation						
	• Integrating the forecast model to the DSS						
	• Developing the advisory generating system to the DSS						
	• Respective experts will provide action oriented advisories under the DSS						
Identification of the threshold level of the weather parameters responsible for insect and disease in different stages of rice crop	• Establish collaboration with the entomology and plant pathology division of BRRI						
	• Laboratory facility development and manpower engagement						
	• Experimentation and field survey						
	• Data collection						
	• Data analysis and reporting						
	• Validation of the experimental findings						
At least 5% rice farmers will be brought under the advisory services	• Establishment of collaboration with DAE						
	• Improving research-extension-farmer network						
	• Development of automated advisory dissemination system under DSS						
	• Providing training to the extension officials and farmers						
	• Conducting demonstration						
The adopted farmers and extension officials will provide their opinions about the service and advisories	• Development of automated feed backing and responding system for farmers, extension officials and researcher in the DSS						
Improving the DSS to make the advisory system automated	• Development of data base from the advisories, experiment, field survey and feedback during 2021-2030						
	• Incorporating the gathered data in the DSS						
More 20% rice farmers will be brought under the advisory services	• Providing training to the extension officials and farmers						
	• Conducting demonstration						
Continuation of the improvement of DSS	• Incorporating continuously gathered data in the DSS						
	• Continuous up gradation and feedback based adjustment of DSS						
Additional 25% rice farmers will be brought under the advisory services	• Providing training to the extension officials and farmers						
	• Conducting demonstration						

LIMITATIONS OF THE STUDY

- Preliminarily, our data did not allow us to identify the exact causes of yield advantages critically. While efforts should be made to identify the exact causes of yield enhancement under WFBAS.
- This study only reflects on a single-season multiple location experiment. It is important to conduct the same experiment in multiple seasons in the farmers' field.

CONCLUSION

The implementation of a weather-based advisory service (WFBAS) has the potentiality to boost rough rice production byenhancing productivity in Bangladesh. The findings of this study show that the adoption of weather-based management practices can increase grain yield by 6.7-21.48% and reduces the cost of productionabout 12%.If only 5% of rice farmers would adopt the WFBAS, the minimum probability of yield increase (6.70%) will add 0.172 million tons of rough rice to the national food basket, the value of which will add about 4478 million BDT to the national GDP. If WFBAS is materialized properly at the entire production system (such as research, extension, and farm), one BDT investment will return 51-73 BDT for the nation. The WFBAS is found very much effective for the farmers as it provides not only the weather forecast information but also technical guidance on the cultivation aspects including timely transplanting and application of fertilizer/ water/pesticides/herbicides/ insecticides. It also saves inputs such as water, manpower, electricity, and fuel, through proper irrigation scheduling. The study has targeted to adopt the WFBAS by 5% farmers at 2030 and projected the outcomes as additional 0.214 million tons national rough rice production that will add BDT 5223 million as the contribution of rice sector to the national GDP. Therefore, the adoption of WFBAS will increase the national agricultural income significantly through increasing rice productivity. Moreover, the projected returns from adopting WFBAS in rice farming will guide the policymakers to take necessary decisions and actions for the establishment, upgrading, and dissemination of this technology to the stakeholders.

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AUTHORS' CONTRIBUTION

NMFR and MSK conceptualized the study; MSK, MUS, NMFR, MARS and MAAM coordinated the study; NMFR developed methodology, assembled all the data sets, performed the statistical analysis, prepared the figures, and wrote the first draft of the manuscript; MCR provided scientific insightsand performed economic analysis; MMH, ABMZH, MMH, TH, MKAB, and MAIK provided advisories for field experiment; NMFR, MIH, MAA, MAAM, MAQ, RA, and AC contributed to managing the location-specific weather forecasts in collaboration with Bangladesh Meteorological Department; MAB, SMQH, MIH, MARS, 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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Adoption Lag Minimization for Increasing Rice Yield

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ABSTRACT

Sustainable adoption of promising technology leads to increase yield and productivity of rice significantly. Yield gap reduction through minimization of adoption cycle of rice technologies is essential to increase food security of Bangladesh. Adoption of promising rice variety required 16±3 years to reach its adoption peak at farm level following the existing dissemination protocol. The specific objective is to find out the ways and means to curtail adoption lag of variety, management practices and rice based technologies for sustainable food security of Bangladesh. The study is accomplished accordingly by reviewing previous works completed on technology adoption; calculation and estimation of future seed demand and supply. Our findings reveal that the average yield gap between actual farm yield and potential farm yield is 20.7%. Seed retention and motivated farmers estimated from the frontline demonstrations of BRRI were 18 and 20%, respectively. Sufficient amounts (128 kg/variety) of breeder seed need to be produced by the concerned research organizations concurrently the variety release process. The seed will be used to execute action plan by setting up 64 adaptive trials (AT) in 64 districts to select location specific suitable variety(s) for rapid dissemination. In the 2nd and 3rd years, 256 kg quality seeds per variety will be required to conduct 128 AT/SPDP in 64 districts. The seed of farmers' chosen variety(s) will be collected, stored, and marketed by the local seed producer or farmers group; and they will provide this information to the extension organization and BRRI. At least 10 to 20% seed selling information will be checked by the concerned scientist of BRRI every year and total seed selling data will be calibrated based on the checked data. Similarly, the next two years' trial data will be collected from conducted trials and associated seed producer/dealer/farmers' club/groups. Then, the concerned research institute will be able to provide a projection of diffusion rate and demand of newly released variety(s) compiling three years data. Based on the authentic reports, the concerned organizations will conduct block, frontline and follow-up demonstrations in collaboration with all the stakeholders. Action plan of research and extension; large scale frontline demonstration of the selected variety(s) with more stakeholders followed by field day, training, and workshop would be the key drivers for effective and sustainable dissemination of technology lead to reduce adoption lag effectively. Combined initiatives and integrated approaches need to be taken nationally to execute the adoption lag minimization plans and model for rapid dissemination of promising technology to doubling the rice productivity. Therefore, popularization and adoption of new technology would be possible within five to seven years instead of 16±3 years.

Key words: Rice variety, yield gap minimization, demonstration, dissemination, varietal and seed replacement rate.

INTRODUCTION

Adoption means the integration of new technology into existing ones; it normally progresses over a period of time through trial and error and, some degree of adaptation (Loevinsohn *et al.,* 2013). Adoption lag is the time (years) needs for a new technology to reach its peak of adoption from its release (Kabir *et al*., 2020). Adoption lag varies from technology to technology depending on its suitability, profitability, environmental and social acceptability. It has been reported that adoption of new rice variety is often required 16±3 years to reach its peak from its release (Kabir *et al.,* 2015). Adoption lag is one of the major factors responsible for the yield gap and plays a vital role in the sustainable food security of a country including Bangladesh. The technology adoption rate remains low in

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developing countries (Mwangi and Kauriuki, 2015; Mottaleb *et al.,* 2015). For example, the popular mega varieties BR11, BRRI dhan28, BRRI dhan29 took about 16 years to attain their highest peak of adoption. These varieties now a day become highly susceptible to pests as those have been in the field for many years.

Varietal replacement is one of the vital concerns and essential to increase rice yield and productivity. Strengthening seed multiplication and distribution system is a must to increase the adoption and dissemination of improved varieties (Singh and Singh, 2016). Improved varietal replacement rates (VRR) and increased seed replacement rates (SRR) have significant effects to minimize adoption lag and also enhance crop productivity. The optimistic role of both VRR and SRR increased the productivity of rice by 27.9% from 2007-08 to 2014-15 that contributed to improving food security in Jharkhand state of India (Singh and Singh, 2016).

Farmers' perspective is very important for sustainable adoption of technology. Varietal performances have significantly influenced the farmers' perception and decision to adopt it. Adesina and Zinnah (1993) rightly mentioned that persuasive decision of adoption or rejection of technologies depends on farmers' perceptions of the appropriateness or inappropriateness of the technologies. In order to improve technical efficiency at farmers' levels, they ought to encourage adopting more effective rice technologies. Abdulai *et al.* (2018) observed that the technical efficiency of adopter farmers increased by 10% compared to non-adopters of rice technologies that have a significant effect on technology adoption. Bangladesh government is very much enthusiastic to reduce adoption lag as well as yield gap. The concerned government organizations (GOs) and also some non-government organizations (NGOs) are working to minimize adoption lag for increasing rice yield. However, those efforts are still far behind to minimize the gap. Lack of smart, competent, and sustainable technology is also an imperative factor to reduce adoption lag. Research organizations are developing a lot of technologies. However, they have not enough information that the technologies are suitable and sustainable for the end-user, or not. Farmers have independent preferences for technology characteristics (Ashby and Sperling, 1992) and these could play a major role in technology adoption. In-substantial dissemination system, lack of smart technology, lack of availability of technology at the root level, land tenure, land size, good communication; socioeconomic factors are responsible for adoption lag of rice technology (Mottaleb *et al*., 2015). Availability of government-approved seed dealers, irrigation facilities, land characteristics, loan facilities; infrastructure, and communications such as roads significantly influence the adoption of modern rice varieties.

The national research institutes (Bangladesh Rice Research Institute-BRRI, Bangladesh Agricultural Research Institute-BARI, Bangladesh Institute of Nuclear Agriculture-BINA, Bangladesh Sugar-crop Research Institute-BSRI, etc.) developed technologies regarding variety, farm machinery, cultivation technique, crop and soil management practices; insect and disease management, etc. They are trying to transfer the technologies to the end-users through public-private partnership (PPP) in collaboration with extension agencies (Department of Agricultural Extension-DAE), other government and non-government organizations. Information and communication technology (ICT) based tools like the websites of the National Agricultural Research and Extension Systems (NARES); social media, electronics, and print media can also be playing a vibrant role in the rapid dissemination of the technology(s) and to curtail adoption lag. Now it is high time to find out the way forward to minimize the adoption lag of technologies for doubling rice productivity by 2030 to achieve sustainable development goals (SDG). Rice is cultivating around 11.42 million hectares (M ha) including 3 seasons (Aus, Aman, and Boro) in Bangladesh (BBS 2018; Karmakar and Ali, 2019) and producing 34.7 million metric ton of cleaned rice which is enough to fulfill the demand of the country (BBS, 2018). However, the self-sufficiency of food is very much vulnerable due to increasing population, declining resources (cultivable land, labor, water, etc.), increasing abiotic (Salinity, drought, cold, etc.) and biotic stress (insect and diseases incidence); natural calamities (flood, flash flood, storm, etc.); and the adverse effect of climate change (Karmakar and Ali, 2019). Around 2.0 million population are adding every year in Bangladesh which required 0.27 million metric tons of cleaned rice annually to feed the growing population (BBS, 2018, Yunus *et al.,* 2019, Karmakar and Ali, 2019). On the other hand, about 0.4% of agricultural land is converting to non-agricultural land every year to meet up the different needs of the growing population (Hasan *et al.,* 2013; Karmakar and Ali, 2019). Moreover, the area under rice cultivation will have to be reduced to accommodate crop diversification as food habit of the people is changing along with increased income. The demand for other food grains has been increasing rapidly from urbanization and upright growth of per capita income of the country. Therefore, it is a great challenge for Bangladesh to feed the huge population from limited land. The use of modern technologies like high-yielding rice varieties along with farm machinery would be the important avenues to reducing hunger and food insecurity in developing countries (Ghimire *et al.,* 2015).

Promoting the adoption of rice technologies in a sustainable way is very important to improve the productivity as well livelihood of the farmers (Asfaw *et al.,* 2012). The net gain from the adoption of new technology is the key determinant of the adoption, inclusive of all costs of using the new technology (Foster and Rosenzweig, 2010). Availability of quality seed of newly released promising variety(s), competent variety, market price; irrigation facility in time, land tenant system are the key dynamics affecting the adoption of modern rice varieties in Bangladesh (Alauddin and Tisdell, 1996; Hossain *et al.,* 2003). Ghimire *et al.* (2015) also stated that the availability of quality rice seeds at the field level had a significant influence on the adoption of newly released promising rice varieties as the farmer would have easy access to the local stores to purchase and cultivate new improved varieties. Therefore, the study was aimed to formulate a guideline to minimize the adoption lag of rice variety and to develop action plan for reducing adoption lag to doubling rice productivity and increase food security.

MATERIALS AND METHODS

Study approach

The study was accomplished accordingly by reviewing previous works and studies completed on technology adoption. Calculation and estimation of future seed demand and supply accomplished through the temporal pathway. The data used in this study were obtained from scientists, extension personnel, and farmers.

Quantification of rice seed

During variety release process, at least 128 kg breeder or quality seeds per variety need to be produced by the concerned research institute for executing action plan. After execution of action plan and varietal diffusion model, adoption lag will be minimized by 5 to 7 years of variety release. Moreover, the seed production and dissemination status of the

Adaptive Research Division was presented through reviewing the annual report 2000-2001 to 2019-2020 of BRRI.

Concept of adoption lag

Adoption means bring it up on one's own or choosing to take it up. Adoption lag denotes to fall behind or follow after a delay to receive technology. Adoption lag is defined by the time difference between releasing technology and its reaches to the adoption peak that expressed as a year (Kabir *et al.*, 2015). The time lag between the release and farm-level adoption of the new varieties needs to be reduced (Singh, 2013).

Conceptual framework for minimizing adoption lag

Adoption system enhancement is very much important to minimize adoption lag. Two major components are the keys to adoption lag minimization. A diagram with major components for adoption lag minimization is given below (Fig. 1).

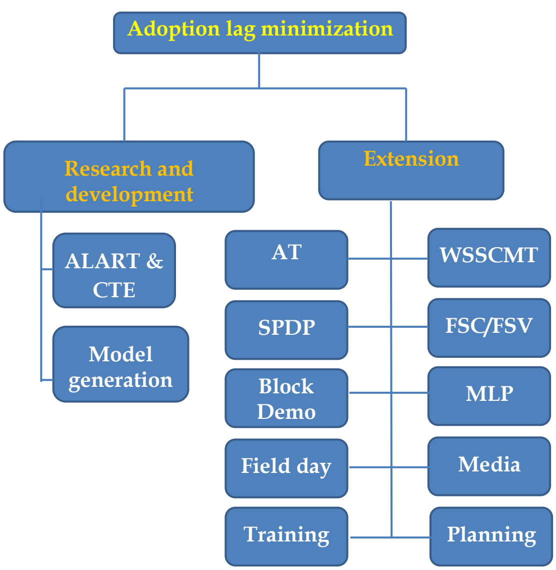

Fig. 1. Conceptual framework for adoption lag minimization.

ALART: Advanced line adaptive research trial; CTE: Component technology evaluation; AT: Adaptive trial; SPDP: Seed production and dissemination program; WSSCMT: Workshop, Seminar, Symposium, Conference, Motivational tour; FSC: Farmer seed center; FSV: Farmer seed village; MLP: Market linkage and price.

RESULTS AND DISCUSSION

Empirical experience of varietal dissemination

Seed Production and Dissemination Program (SPDP) is a fruitful program launching by the Adaptive Research Division (ARD) of BRRI for rapid dissemination of modern rice variety that could be an example for other institutes. Figure 2 shows that after releasing a technology, it required 16±3 years to reach its peak from its release (Kabir *et al.*, 2015; Karmakar *et al.*, 2018). The yield gap is another major constraint to achieving the potential yield and doubling the rice productivity. Figure 3 indicated that the gap between potential farm yield and actual is around 20.7% (Kabir *et al.*, 2015). Therefore, yield gap reduction by 10% would be a milestone to doubling rice productivity.

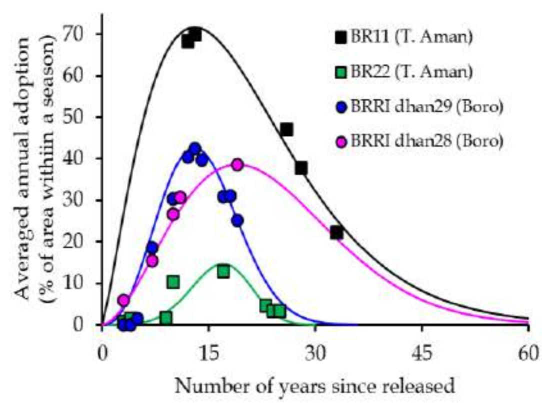

Fig. 2. Adoption curve of four BRRI released rice varieties in three seasons. The curves were well fitted using three parameters Weibull equation using data from Kabir *et al.*, 2015.

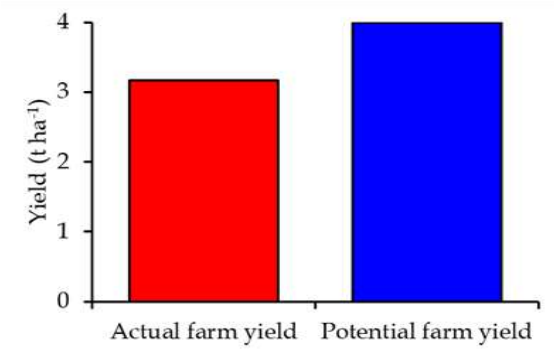

Fig. 3. The actual farm yield and potential farm yield of clean rice in Bangladesh, showing the yield gap of 0.83 t h^{-1} or 20.7% (Adopted from Kabir *et al*., 2015).

For example, ARD of BRRI has the mandate to validate technology(s) developed by different research divisions of BRRI and to transfer the technology. ARD is executing the mentioned activities like technology validation and technology dissemination effectively. Department of Agricultural Extension (DAE) is mainly responsible for technology diffusion; however, the existing national system for technology transfer is lengthy and time-consuming. Therefore, ARD has set up a small scale of adaptive trials and frontline demonstrations of newly released rice varieties to enhance the dissemination process. We reviewed the dissemination activities of ARD from 2000-2001 to 2019-2020 conducted throughout the country. Most of the rice varieties developed by BRRI were demonstrated at farmers' fields during the period. A total of 4254 metric ton grain was produced of which 804 tons (18%) were preserved as seed for the use of succeeding season that was contributed significantly to the diffusion of the varieties (Fig. 4) and the farmers' motivation was 20% (Fig. 5). We need to minimize adoption lag by reducing the yield gap by utilizing all sorts of tools to bridging up the adoption lag and increase rice yield and productivity.

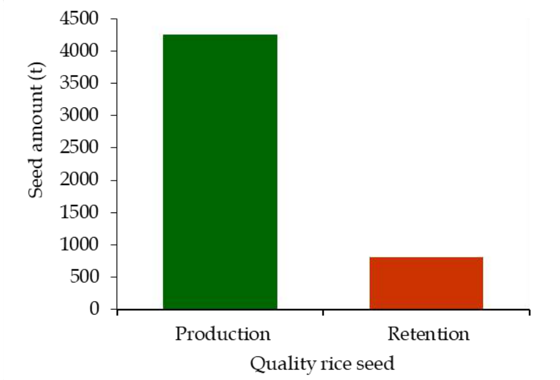

Fig. 4. Quality seed production and retention (18%) by farmers during 2000-2001 to 2019-2020 through demonstration conducted by the ARD of BRRI, Gazipur.

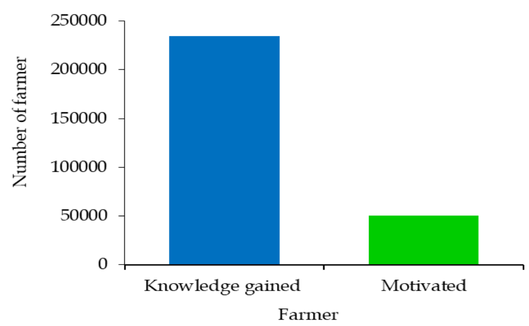

Fig. 5. Knowledge gained and motivated farmers (20%) during 2000-2001 to 2019-2020 through demonstration conducted by the ARD of BRRI, Gazipur.

Action plan for varietal adoption lag minimization

An action plan is very much important for the proper implementation of a program and to reach the target. Therefore, we formulated an action plan for rice technology adoption through to 2050 (Table 1). Several coordinated programs need to be executed for the adoption lag minimization. The prime factor for adoption lag is the dispersion rate of the technology during the diffusion stage of first three years' adoption rate after the release of the technology. If this diffusion stage can suggest quick acceptance of technology, then its adoption rate should be high and adequate preparation might decrease adoption lag.

Table 1. Action plan for adoption lag minimization

Theme	Programme	Action
Research and Development	ALART and CTE	• Authentic, independent and multi-stakeholder evaluation (Modification and acceptance of product profile) • Validation and recommendation of advanced breeding line
	Model generation	• Identification of field applicable technology dissemination (FATD) model • Calibration and validation of FATD model
Extension	AT	• Validation and selection of location-specific suitable variety and component technology
	SPDP	• Location-specific demand-based seed production • Need-based seed distribution
	Block Demo	• Awareness building and bulk seed production
	Field day	• Create awareness to mass population
	Training	• Trained up of extension personnel and lead farmers • Trained up of community influencers (Agriculture trader, Local leader, Teachers, Imam, etc.)
	WSSCMT	• Motivation through interaction and knowledge sharing
	FSC/FSV	• Easy access to quality seed at farm level
	MLP	• Ensure fair price
	Media	• Rapid dissemination of information flow
	Planning	• Feedback from stakeholders and variety diffusion rate report

ALART: Advanced line adaptive research trial; CTE: Component technology evaluation; AT: Adaptive trial; SPDP: Seed production and dissemination program; WSSCMT: Workshop, Seminar, Symposium, Conference, Motivational tour; FSC: Farmer seed center; FSV: Farmer seed village; MLP: Market linkage and price

Technology validation and evaluation

BRRI tests the adaptability and suitability of the advanced breeding lines or technology through conducting a trial named advanced line adaptive research trial (ALART) or component technology evaluation (CTE) at only a few (8 to 12) locations throughout the country in different agro-ecological conditions. But it is needed to conduct the trials at more locations covering all the agro-ecological zones of the country to investigate location-specific adaptability and suitability to generate more information about the technology, especially for a new genotype.

Evaluation of new genotype or technology is very much important. Authentic ALART/CTE can trigger adoption rate largely and subsequently reduce adoption lag. Therefore, proper evaluation based on authentic data collected by following appropriate methodology will be ensured during this process. Standard check variety/technology is to be selected rationally covering specific objectives. After evaluation, a recommendation will be based on authentic results with appropriate statistical analysis. The product profile of the advanced line(s)/technology will be supplied before the setup of the trial with judicial check(s) selection. For example, if the objective of the new advanced line is to replace BRRI dhan28, then the product profile should be better than BRRI dhan28 in all respect and should also supersede the last improvement of the similar genotype like BRRI dhan88 and/or BRRI dhan96.

All the concerned beneficiaries will be involved in the evaluation of new technology to find its suitability in the existing circumstances (Mwangi and Kariuki, 2015). Therefore, all the stakeholders like farmers, extension agencies, NGOs, companies, seed producers, dealers, millers, traders, etc. will be invited during the evaluation of technology. They will evaluate the technology for choosing the better one and subsequently, the technology(s) will be more sustainable. In addition, awareness will be built up during the evaluation of the technology which might trigger adoption after release. Moreover, multi-stakeholders' independent evaluation will make the process more authentic, transparent, reliable, and sustainable.

Model for technology adoption

In a technology dissemination process, farmers (ultimate users), producers (seed or equipment), extension personnel, and researcher are very closely related and interconnected for technology adoption (Fig. 6). If one of the stakeholders becomes inactive then, adoption will be interrupted. For example, in an AT or SPDP, if new improved varieties are demonstrated along with the local popular check variety in the same piece of land with the appropriate production technology of the respective varieties, then the varieties will show their yield potentiality. Extension personnel will select a local seed producer or a farmer's group like integrated pest management (IPM) club integrated crop management (ICM) club, common interest group (CIG), etc. who will collect the seed produced in AT or SPDP. The researcher will select the production package of the varieties to be followed. Seed producers and extension personnel will select suitable land and farmer for the trial. Local seed producers will collect seeds of farmers' selected variety(s) and will sell them in the next year. This model is formulated by Rahman *et al.* (2020). Seed selling rate will indicate the dissemination rate of the variety.

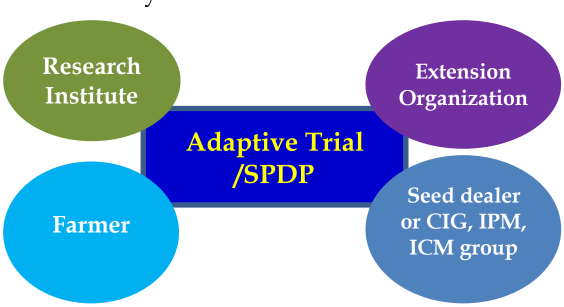

Fig. 6. Mode l: demonstration with 4-Stakeholders.

Model for varietal diffusion

In the first year of variety release, a number of AT or SPDP will be set up based on the availability of seed. For example, if 128 kg seed/variety is available, then 64 trials will be set up in 64 districts. In 2nd and 3rd years, 128 AT/SPDP will be conducted in 64 districts @ 2AT/SPDP per district. Then 256 kg seed/variety will have to be supplied by the research institute.

The extension organization will supervise the trials along with BRRI. In every trial, a field day will be organized to know the feedback of farmers and other stakeholders. The seed of farmers' chosen variety(s) will be collected, stored, and marketed by the local seed producer or IPM/ICM/CIG farmers group and they will provide this information to the extension organization and BRRI. At least 10 to 20% seed selling information will be checked by the concerned scientist of BRRI every year and total seed selling data will be calibrated based on the checked data. Similarly, the next two years' trial data will be collected from conducted trials and associated seed producer/dealer/farmers' club/groups. After three years, compiling all the data, the researcher will be able to show the rate of dissemination of a variety during the diffusion stage (Fig. 7). Based on the reports of diffusion stage, the research institute will be able to give a projection of adoption lag of the new variety(s) indicating the role of other national components like Bangladesh Agricultural Development Corporation (BADC), Seed Certification Agency (SCA) and Department of Agricultural Extension (DAE), etc.

Adaptive trial for varietal adoption

Sufficient quantitative information/data are required for varietal replacement decisions from a greater number of trials across the country. Therefore, an adequate number of adaptive trial (AT) or head-to-head adaptive trials (HHAT) need to be conducted throughout the country for generating sufficient information leading to massive scaling up the decision of newly released varieties in the target environments. Moreover, the seed dissemination system in Bangladesh is also slow and lingering. Therefore, AT will also play a significant role to replace old mega varieties with the latest ones and it also has a vital contribution for rapid dissemination. Farmers' rally and field day will be conducted on the performances of modern rice varieties. Suitable and better performing variety(s) will be selected by the farmers from those HHAT of specific environment for large scale diffusion. Farmers also are suggested to preserve quality seeds of the selected variety(s) for next year's use. On the other hand, seed-producing agencies will multiply seeds of the promising ones.

Awareness build-up during advanced genotypes evaluation

Research organizations test the adaptability of the advanced breeding lines through conducting trial named advanced line adaptive research trial (ALART) at only 8 to 10 locations throughout the country due to resource constraints. But it is essential to conduct the trials at more locations covering all the agro-ecological zones of the country to investigate location specific adaptability and to generate more information about the advanced genotypes. Awareness need to be buildup during evaluation of the genotypes evaluated under ALART. It is therefore important that the end users should be involved in the evaluation of new technology to be introduced to farmers and they find its suitability to their circumstances (Mwangi and Kariuki, 2015). All the stakeholders like farmer, extension agencies, NGO, company, seed producers, dealer, miller, trader etc. will be invited at maturity stage of the crop for evaluation. They evaluate the genotypes and chose the better ones for specific environment, and then the technology(s) will be more sustainable.

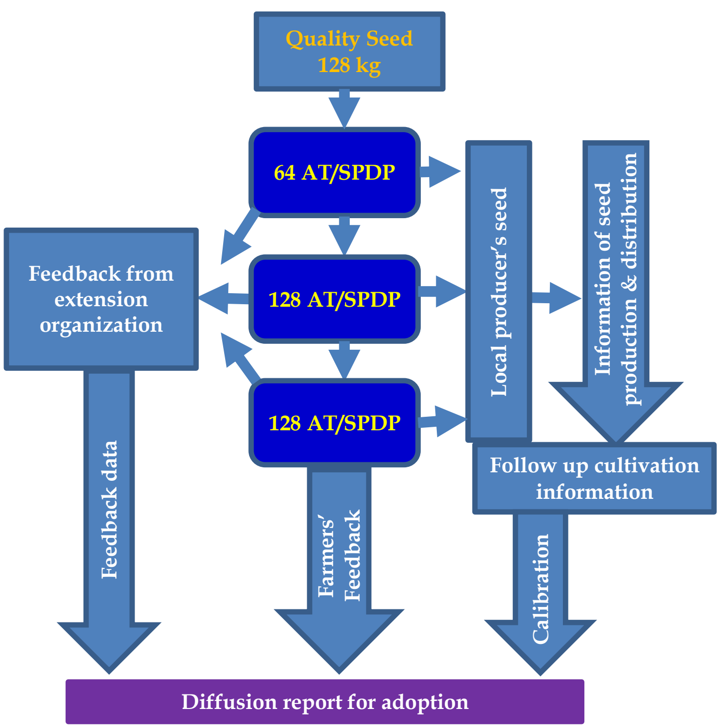

Fig. 7. Model of varietal diffusion to guide future adoption plan.

Component Technology Adoption

A good variety without appropriate management, yield tends to zero. Consequently, management practices are very much important to get higher yield and to achieve higher productivity of a variety. The research institutes developing diversified varieties based on different agro-ecological zones (AEZ), environments (salinity, drought, flood, submergence, water stagnant, cold etc.), product profile, cropping pattern and so on. Growth duration of the varieties varied highly ranged from 100 to 170 days (BRRI, 2020). Therefore, variety specific management (VSM), location specific management (LSM), Integrated pest management (IPM), Integrated Crop management (ICM), Line Logo Perching (LLP) etc. are now time-demand to obtain optimum yield and productivity. For example, BRRI dhan75 is low input responsive short duration (105-110 days) green super rice. Optimum seedling age for transplanting of this variety would be 15 to 20 days. Sometimes, farmers transplant older seedlings (30-40 days) of this variety and panicle emerged within few days after transplanting; finally yield reduced drastically. Therefore, we have to follow good agricultural practice (GAP). Crop management practices vary from one AEZ to another AEZ. For example, agronomic (crop and fertilizer) management for saline environment must be different from drought environment. Therefore, variety and location specific managements need to be followed to achieve higher yield and productivity.

Seed production and dissemination program (SPDP)

Demonstrations with 2-stakeholders (extension agencies-farmers) and 3-stakeholders (research organization-extension agencies-farmers) are being practiced in Bangladesh (Fig. 8). However, the effectiveness and sustainability of technology transferred through these models are not at par level. Therefore, including more stakeholders for the demonstration and adoption of technology will be more effective and sustainable.

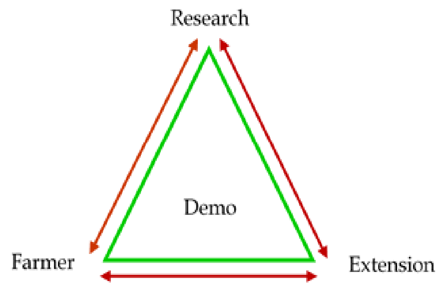

Fig. 8. Model demonstration with 3-Stakeholders.

Demonstrations of the selected varieties/technology(s) in collaboration with 4-stakeholders (research organization-extension agencies-farmers-seed dealers/traders), 5-stakeholders (research organization-extension agencies–farmers-seed dealers/traders-formal seed agencies) and 6-stakeholders (research organization-extension agencies-farmers-seed dealers/traders-formal seed producing agencies-seed certification agency) (Fig. 9) will be more effective instead of the existing 2- stakeholders (Extension agencies and farmers), and 3-stakeholders (research organization-extension agencies-farmers). Formal seed producers of Bangladesh (GO, NGO, and company) are producing and supplying almost 50% rice seed, and the rest of the seeds come from informal systems (farmers) (Iqbal and Toufique, 2016; Karmakar and Ali, 2019). Therefore, quality seed production and storage at the farmers' level are equally important. Sometimes dealers are the key factor to select variety/technology/ management options to be used by the farmers. Consequently, the involvement of seed dealers in the demonstration will speed up adoption. We encourage farmers to produce quality rice seeds through SPDP. Accordingly, they can produce and use their seed next season. But farmers could not sell the seeds that remained after their use. In this channel, seed dealers can buy quality seeds from the farmers and those will be sold to farmers next year. Then farmers will be benefitted financially through selling quality seeds.

Block demonstration

Demonstration of a new variety conducted generally 1 to 3 bigha (33-99 decimal). But it is not able to create a significant impact on the farmers, millers, businessmen, and consumers. Therefore, bigger size demonstrations like 1.34 to 13.4 hectares (10 to 100 bigha) have to set up in a place that will have a remarkable impact to change the attitudes of the stakeholders and to minimize adoption lag.

Field day

It is very important to demonstrate the results and field performance of promising rice varieties to the stakeholders. Then farmers and other stakeholders could easily be understood and build up confidence about the technology by "Seeing is believing" through Field day. Field day creates awareness and interest about the varieties and other technologies among farmers, local leaders, elite persons, extension personnel, seed dealers/traders. Consequently, large numbers (20% of total demonstration) of a field day on the performance of the varieties need to be conducted. Interested farmers and traders will be identified from field days to produce seeds of selected varieties.

Training

Large numbers of training on modern rice variety, crop management practices, seed to seed technology (seed production, processing, storage, and packaging); and other technologies are very much important for farmers and extension personnel to update their knowledge and skill. A rice production manual having all the practical aspects of seed-to-seed technology will be provided in the training programs.

The training will be operated in collaboration with BRRI and extension agencies for the sustainable adoption of technology. Generally, most of the farmers' training is conducting at upazila level. The main drawback in existing training is that the same farmers/participants receiving the same training several times while a vast number of farmers are left behind without getting updated training on rice technology. An intervention with innovation is now the time-demand to overcome this problem. The farmers' training on agricultural technology will be organized and conducted at the root level (village level) instead of upazila-based training. This effort will increase knowledge, skill, and updated information about the technology. It will also help to enhance technology diffusion and adoption to the end-users reducing adoption lag.

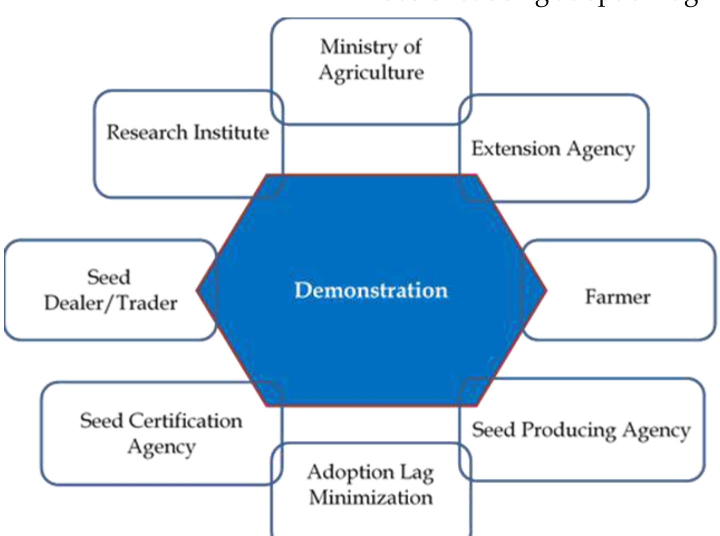

Fig. 9. Model demonstration with 6-stakeholders.

Workshop/Seminar/Symposium/Conference

Workshop/Seminar/Symposium/Conference among all the stakeholders will have a significant effect to increase adoption of newly released variety(s) as well technology. Workshop on rice technology will be arranged on an agricultural region basis and also centrally. Location/region specific many problems and prospects will be come-out in the workshops. All the stakeholders will be benefitted mutually through the workshop and adoption lag will be minimized through steps taken based on the recommendations.

Motivational tour

Technology adoption and dissemination significantly vary from region to region, location to location; even in a small distance. Motivational tours of the farmers to observe the successful adoption of technologies have a significant impact on adoption. Farmers of a region brought out another region/location could observe physically the technology and its technical know-how. They discuss with the adopted farmers and can learn the success story. Adoption level could be enhanced in this process when farmers heard and observed about the technology from other farmers and then, their confidence level must be improved to accept and practice the technique.

Farmers seed center/village establishment

Nowadays farmers are very much reluctant to grow and preserve seed at the farm level. They are habituated to buy packet seed from the market/dealers. The establishment of Farmers Seed Center (FSC) /Seed village/Technology village is another effective option to make availability of quality seeds of newly released promising rice variety and other technologies at farm level for rapid dissemination (Kabir *et al.*, 2019). FSC builds up storage facilities of seeds and also increases the availability of quality seeds at the field level. It will change farmer's attitudes and perceptions regarding seed storage and the use of the self-stored seed. It will also encourage other farmers for storing and using of own quality seed.

Market linkage and price

Market linkage and price of rice are the imperative determinants for adopting a variety and technologies. Block demonstration linking with all the stakeholders like farmers, extension agencies, researchers, seed producers, seed dealers, rice millers, and businessmen will create a marketing channel of rice. Government is very much enthusiastic to increase rice prices and decrease production costs. Rice price needs to be increased at par level and it should be higher than the production cost. Then farmers will be encouraged to produce more rice with proper care that would have positive effects to increase adoption.

Publications and media coverage

Print and electronic media can play a vital role to build up awareness about the technology. Media coverage of promising technologies need to be increased to enhance technology adoption. Then suitable technologies will rapidly be disseminated to the farmers and stakeholders. Leaflets, booklet, journal, book, etc. on smart technologies will be published by BRRI which will increase technology adoption directly and indirectly. Social network effects are important for individual decisions. Farmers can share information and learn from each other in the particular context of agricultural innovations (Uaiene *et al.*, 2009). Usage of web portals and websites of the concerned organizations; and social media will have a significant role to cognizant about the technologies to mass populations that enhance adoption through disseminating rice technologies rapidly.

Planning for rapid adoption

The diffusion stage is very important for the adoption of a variety or technology. In the first three years of a variety release, a number of demonstrations will be conducted throughout the country following the model demonstration with four stakeholders shown in Figure 6. Then the feedback of the stakeholders, seed production and selling information of local seed producer or farmers' group (IPM/ICM/CIG), follow up cultivation information will provide much information about dissemination and spreading of the variety (shown in Figure 7). After three years, compiling and analyzing all the information, the researcher will prepare a report of the diffusion stage mentioning the rate of dissemination of the variety. In the report, BRRI will give a projection of the adoption lag of the new variety(s) indicating the specific role of other national organizations like BADC, SCA, DAE, etc. Collaborative and collective efforts of national organizations based on the recommendation and suggestion of the report will reduce adoption lag largely.

An effective seed system denotes the activities of quality seed multiplication, storing and distribution, and the use of these quality seeds by farmers for growing crops. It has close linkages with other systems, particularly research and extension (Singh and Singh, 2016). The role of the actors in the seed systems is very imperative to reduce adoption lag by enhancing seed availability to the farmer. The present seed system in Bangladesh is slow and lingering. The formal seed producers/agencies produce seeds of popular varieties as a business model. The new variety takes many years for getting its popularity in the existing seed system. It is now high time to make an intervention in this system for rapid dissemination of newly released promising variety.

For rapid popularization, extension agencies will estimate upazila-wise demand of seed for the newly released potential rice cultivars through conducting adaptive trials of the newly released varieties in collaboration with research organizations in the 1st year of variety release. After getting a positive response of varietal acceptance by the farmers, the extension agencies will inform the requirement to the seed-producing agencies at well-ahead of commencing seed production program for the following seasons with an assurance for the marketing of the seed (Kabir *et al.*, 2019). A model of an improved seed system is presented in Figure 10 for rapid dissemination and adoption lag minimization of newly released rice variety(s).

Implementation strategy

The activities will be executed through a public-private partnership (PPP) having strong collaborations and linkages among the stakeholders (Ministry of Agriculture, research institutes, extension agencies, seed producing agencies, seed certification agency, farmers, seed dealers/traders and millers).

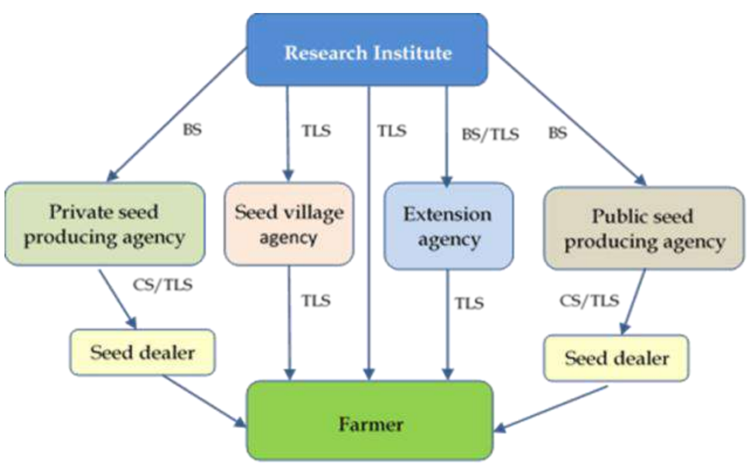

Fig. 10. Seed system model for rapid dissemination and adoption lag minimization. Note: BS=Breeder seed, CS=Certified seed and TLS=Truthfully labeled seed

CONCLUSION

Technology dissemination with integrated approaches like an authentic and multi-stakeholder evaluation of advanced genotypes or component technology, adequate field applicable demonstration of the technology, proper adoption plan based on diffusion information, and speedy availability of seeds to farmers would boost up technology adoption for minimizing adoption lag. Adoption of newly released rice variety would be possible within five to seven years if the formulated action plan and adoption lag minimization models could be practiced. Combined efforts of farmers, researchers, extension personnel, and the Government of Bangladesh would be enabled to minimize adoption lag by 2030 that could be a vital role in doubling the rice productivity and sustainable food security.

RECOMMENDATION

- Production of breeder, foundation, certified and quality seeds; and their supply need to be ensured by the concerned organizations in time.
- Action plan need to be primed to execute the strategies and model for adoption lag minimization and rapid dissemination of promising technology(s).
- Varietal replacement rate (VRR), seed multiplication rate (SMR) and seed replacement rate (SRR) of new varieties have to be increased at par level.
- Strengthening linkage among research institutes, extension agencies, farmers and public-private partnership (PPP).
- Manpower of research institutes especially for BRRI should be increased.
- Training and workshop on modern rice technology need to be organized and executed in collaboration with all the stakeholders.

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Intensification of Cropping through Utilization of Fallow Period and Unutilized Land Resources in Bangladesh

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ABSTRACT

Unavailability of suitable technologies including stress-tolerant cultivars, management options, irrigation facilities as well as extension supports are the key challenges for intensification of cropping through horizontal and vertical extension approaches. This study assesses the potential for increasing rice production through a horizontal extension approach. Historical and projected trend of area and production of rice, major cropping patterns and cropping intensity, as well as expert opinion, were the basis for extrapolation of the intensity of cropping by 2030. The analysis shows that about 1.52 M ha area with fallow period of the existing major cropping patterns and 0.65 M ha fallow land is potential for additional rice cropping. Resulting from that about 5.8 million tons additional rice can be added to total rice production in the country. An inclusion of a rice crop in certain percentage of the existing major cropping patterns, such as Boro-Fallow-T. Aman (25%), Boro-Fallow-Fallow (50%) and Fallow-Fallow-T. Aman (40%) may contribute, respectively 1.38 million tons, 1.57million tons and 0.80 million tons of rice in the total rice production. Besides, the addition of a certain percentage of cultural waste (50%), marshy land (25%), newly developed char land (50%), and *Jhum* (60%) and other extrapolation areas of Chittagong Hill Tract, respectively may contribute 0.4 million tons, 0.25 million tons, 0.34 million tons and 0.06 million tons rice in the total rice production. Strategic policy supports are required for implementing appropriate action plans to achieve the goals.

Key words: Utilizing fallow period, current fallow, culturable waste, increase rice area, rice production

INTRODUCTION

Government of Bangladesh in its sixth five years plan suggested both the horizontal (i.e., area expansion) and vertical (i.e., yield increase) extension approach to increase the food production in the country to meet up the demand for the growing population from the shrinking land resources. The country has to produce 44.6 million tons of clean rice by 2050 for 215.4 million populations (Kabir *et al.*, 2015). There is a limited opportunity for increasing crop production in the favourable ecosystem through a vertical extension approach as cropping intensity in the area has reached about 200% (BBS, 2017b). On the other hand, there is an opportunity for increasing crop production through a horizontal extension approach in the stress-prone ecosystems in particular in the saline coastal, deep water, haor, char land ecosystem, and Chittagong Hill Tracts (CHT) where arable land is less intensively used than a favourable ecosystem. The rice is cultivated (i) in the three seasons in Bangladesh, (ii) occupies about 75% of the total cropped areas of the country (BBS, 2017b), and (iii) potential to cultivate on the slope of the hill to the area with stagnant water up to three meters.

It can be noted that crops other than rice are not suitable for cropping in the fields with stagnant water (Nasim *et al.*, 2017). Therefore, rice has the potential for being introduced both in the favourable and unfavourable ecosystem for enhancing crop production in the country. However, the unavailability of suitable technologies including stress-tolerant cultivars and management options, irrigation facilities as well as extension supports are the key barriers

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for increasing cropping in the stress-prone ecosystem through increasing cropping area. Understanding the existing cropping patterns, potential technologies, and strategies for improving the system productivity in a specific rice ecotype are the major concerns for boosting up total rice production. Nevertheless, none of the studies found to intensively assess opportunities for increasing rice production by implementing both the horizontal and vertical extension approaches. Thus, this study assesses the potential for increasing rice production through a horizontal extension approach by the inclusion of a rice crop in the fallow period in the major cropping patterns and utilizing current fallow and culturable waste both in the favourable and stress-prone ecosystem. Followed by the introduction, description of method is presented briefly. Thereafter, land utilization patterns, factors that contributed to rice production, extrapolation of total rice production by 2030 and conclusions are outlined.

METHODOLOGY

Secondary data were used for the study and mainly collected from different published sources including the Statistical Yearbook of Bangladesh (BBS, 2017a) and Year Book of Agriculture Statistics (BBS, 2017b). The future trend of various data until 2030 was projected based on historical data. Either 1969-70 or 1975-76 was considered as a baseline for the projection of future trends of different indicators subject to availability. Most of the data showed linear change over time; therefore, the best fit linear regression model was used to predict the future trends of different indicators to identify the way of boosting up rice production. The historical and projected trend of area, production of rice, and cropping intensity, as well as expert opinion, were considered as a basis for extrapolating the percentage of area is potential for inclusion a rice crop in the fallow period of the major cropping pattern and percentage of fallow land could be under rice cultivation in 2030.

RESULTS AND DISCUSSION

Land utilization pattern

On average about 75% of the total cropped area of Bangladesh is used for rice cultivation (BBS, 2017b). Net cropped area of the country has decreased to 7.73 M ha in 2018-19 and will be decreased to 7.54 M ha in 2030 (Fig. 1) as the arable lands are used for infrastructural development for shelter of the growing population, industries, and other purposes.

Despite that total rice and non-rice cropping area or total cropped area has been increasing, and will be increased in the future (Fig. 2) because of increasing cropping intensity. It was observed that cropping intensity increased to 195% in 2016-17 at the rate of 0.65% and will be 215% by 2030 from 147% in 1969-70 (Fig. 3).

It indicates that some single-cropped areas transformed to a double-cropped area, some double-cropped areas to the triple-cropped area, and some triple-cropped areas to quadruple cropped area by accommodating rice or non-rice crops in the cropping patterns. It was observed that a single cropped area shows a decreasing trend under historical (1975-76) and future conditions (2019/20-2030/31). On the contrary, the doubled cropped area shows an increasing trend under historical conditions (until 2017-18) and decreasing trend under future conditions. Besides, tripled cropped area shows an increasing trend under historical (1975-76) and future conditions (2019-20 to 2030-31), consequently cropping intensity in the country will be increased further in the future (Fig. 3). It can be noted that cropping in the country substantially changed because of the development and dissemination of new generation short duration rice and non-rice cultivars to fit into the fallow period in the existing single and two crops-based cropping patterns. Percent contribution of rice and non-rice crops to total cropped areas showed an opposite trend (Fig. 8). Additionally, the availability of other green revolution technologies including chemical fertilizers, pesticides, and irrigation facilities also contributed to increasing cropping intensity. For instance, irrigated Boro rice in the dry season was cultivated in about 4.86 M ha due to the availability of irrigation facilities (BBS, 2017b).

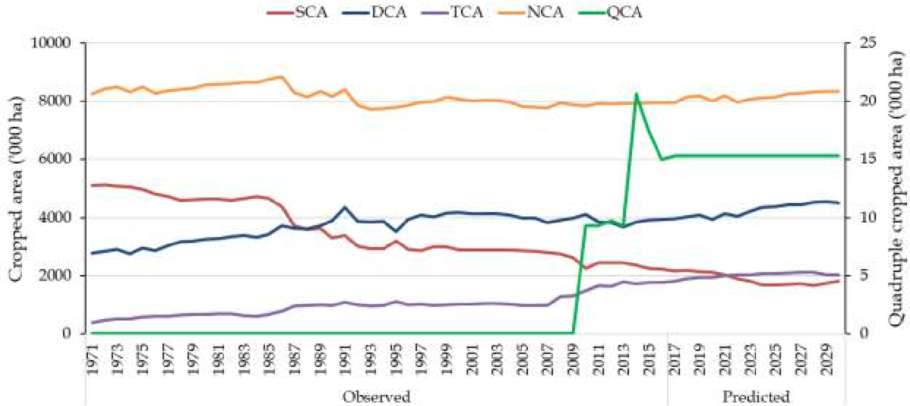

Fig. 1. Trend of single cropped area (SCA), double-cropped area (DCA), triple cropped area (TCA), quadruple cropped area (QCA) and net cropped area (NCA).

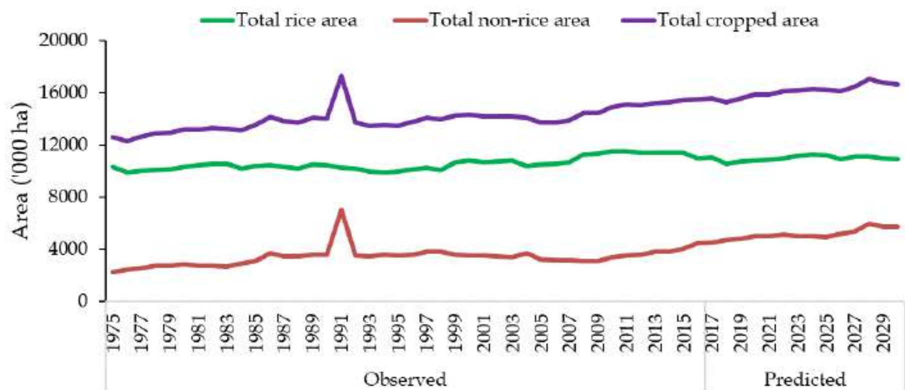

Fig. 2. Trend of total cropped area, total rice area and total non-rice area during 1974-75 to 2030-31 in Bangladesh.

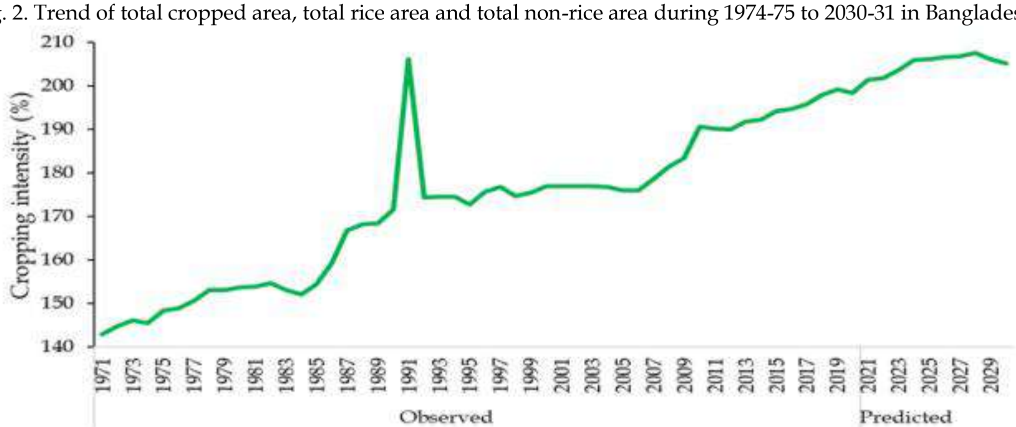

Fig. 3. Trend of cropping intensity during 1970-71 to 2030-31 in Bangladesh.

Factors contributed in rice production

Total rice production in the country increased to 34.07 million tons in 2017-18, which is about three times higher than that of baseline in 1975-76 (Fig. 4). Increased total rice cropped area (Fig. 2) and yield (Fig. 5) are jointly contributed to an increase in total rice production. We estimated the contribution of total rice area increase in total rice production through considering current rice yield (3.12 t ha^{-1}) for 9.68 M ha total rice cropped area in 1975-76.

Total rice production in 1975-76 at the current yield is 30.21 million tons, which was 4.15 million tons lower than total rice production (34.36 million tons) in 2017-18. This analysis indicates that 4.15 million tons of rice production have increased only because of increasing total rice cropped areas for increasing cropping intensity. Thus it is evident that it is possible to increase total rice production by increasing cropping intensity.

The contribution of increased yield on total rice production was estimated by calculating the contribution of better genotype, agronomic management, chemical fertilizer, and irrigation. The estimated baseline total rice production for 9.68 M ha at 1.22 t ha^{-1} yield for local cultivars in 1975-76 was 11.81 million tons. The contribution of higher yield potential modern cultivars, agronomic practice, chemical fertilizer, and improved irrigation facilities in total rice production (18.4 million ton) was estimated by subtracting baseline total rice production (11.81 million ton) from the extrapolated total rice production (30.21 million ton) in 1975-76 at current yield. Figure 6 presents baseline total rice production (11.81 million tons), increased rice production for increased total rice cropped area (4.15 million tons), and the adoption of higher yield potential modern cultivars, agronomic practice, fertilizer, and irrigation application (18.4 million tons). The results indicate that the adoption of green revolution technologies in particular modern cultivars, chemical fertilizers, and irrigation substantially contributed to increasing total rice production followed by increased area. Therefore, it can be claimed that it is possible to increase total rice production through the adoption of higher yield potential better genotype, and improved agronomic practices.

Fig. 4. Trend of total rice production during 1969-70 to 2030-31 in Bangladesh.

Fig. 5. Trend of total rice yield during 1969-70 to 2030-31 in Bangladesh.

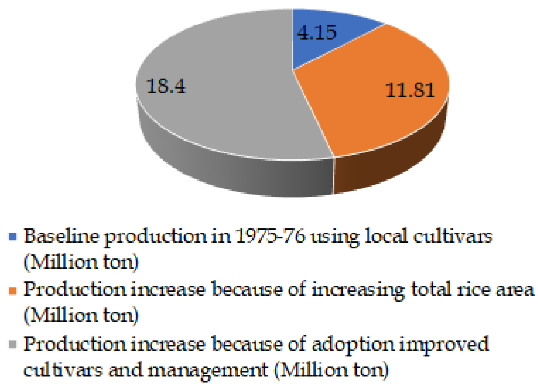

Fig. 6. Contribution of rice area intensification, high yielding variety and modern management practices and base production by local varieties to total rice production in Bangladesh.

Extrapolation of total rice production

In this study, total rice production in 2030 is extrapolated based on (i) increased total rice cropped area through increased cropping intensity by adopting another rice crop in the fallow period in the existing major cropping patterns and (ii) bringing the current fallow and culturable waste area under rice cultivation will increase rice production. Likewise, it is reported that there is potential for enhancing rice production by introducing rice in the under-utilized areas in Barishal, Sylhet, Khulna, and Jashore (Kabir *et al.,* 2020). The following measures could facilitate increasing total rice production to achieve SDGs.

Firstly, from the afore mentioned discussion, it is understandable that there is an opportunity for boosting total rice production in the country through the inclusion of a rice crop in the existing cropping pattern. Table 1 presents the fifteen most dominant cropping patterns in Bangladesh. It was observed that there is a notable scope for increasing cropping intensity in the country through the inclusion of one or two rice and non-rice crops in the existing cropping pattern by utilizing available technologies and developing suitable cultivars and component technologies. Boro in the dry season followed by fallow in the early wet season and T. Aman in the wet season was the most dominant cropping pattern in the country, covers about 27% of the total net cropped area. It indicates that about 27% of the total net cropped area in the country remains fallow in the early wet season for about four months in between Boro and T. Aman rice.

On the other hand, despite the reduction trend of Aus area (Fig. 7) the country has a higher yield potential of medium growth duration Aus rice cultivar (BRRI dhan48 and BRRI dhan83) for fitting into the cropping pattern. Additionally, there are facilities for supplementary irrigation in most areas for establishing Aus rice on time if no rain occurs on time, and the government has given special attention to developing surface water irrigation facilities in the coastal areas through re-excavation of canals. Thus, it can be claimed that there is an ample opportunity for boosting rice production in the country through the inclusion of another rice crop in between Boro and T. Aman subject to ensuring the availability of seed for Aus cultivars, the extension supports, and most importantly access to the fair price of rice grain to make it economically viable. If we can bring 20% of the total area of the cropping pattern (0.576 M ha) under Aus rice cultivation that can add 1.38 million tons of rice in the total rice production with a 3.0 t ha^{-1} yield. Similarly, there is a potential for the inclusion of Boro rice in the 5th most dominant cropping pattern (Fallow-Aus-T. Aman) in some areas for increasing total rice production by developing irrigation facilities.

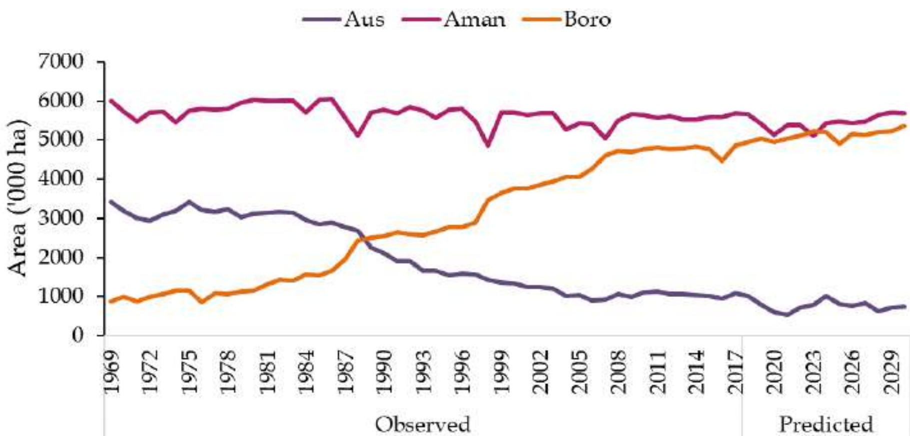

Fig. 7. Trend of Aus, Aman and Boro area during 1969-70 to 2030-31 in Bangladesh.

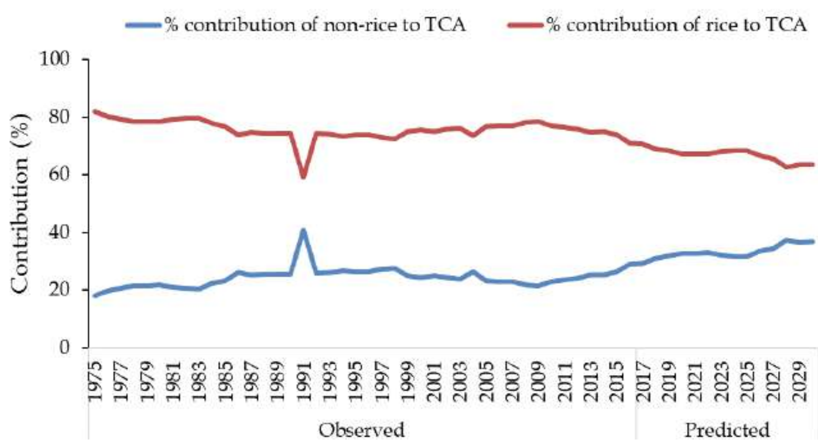

Fig. 8. Trend of percent contribution of rice and non-rice area to total cropped area during 1974-75 to 2030-31 in Bangladesh.

Table 1. List of dominant cropping patterns in Bangladesh, 2014-15.

Cropping pattern	Area (ha)	NCA (%)	District (No.)	Upazila (No.)
Boro-Fallow-T. Aman	2306,005	26.919	63	426
Boro-Fallow-Fallow	1139,530	13.302	59	342
Fallow-Fallow-T. Aman	509,480	5.947	36	162
Boro-Aus-T. Aman	209,015	2.440	47	177
Fallow-Aus-T. Aman	193,275	2.256	30	108
Mustard-Boro-T. Aman	184,620	2.155	51	203
Boro-B. Aman	183,070	2.137	32	113
Potato-Boro-T. Aman	180,380	2.106	33	115
Wheat-Jute-T. Aman	147,210	1.718	43	216
Veg.-Veg.-Veg.	143,270	1.672	61	283
Mustard-Boro-Fallow	143,130	1.671	37	112
Grasspea-Fallow-T. Aman	108,150	1.262	25	80
Maize-Fallow-T. Aman	101,460	1.184	39	126
Wheat-Fallow-T. Aman	90,910	1.061	39	100
Mungbean-Fallow-T. Aman	89,650	1.047	22	70

Source: Adopted from Nasim *et al.*, 2017. Note: NCA= Net cropped area, Veg.= Vegetables

Secondly, Boro in the dry season, followed by fallow in the early wet season, and the wet season is the second most dominant cropping pattern, covers about 13% of the total net cropped area (1.134 M ha). Besides, mustard in the dry season followed by Boro in the dry season and fallow in the wet season is the eleventh most dominant cropping pattern, covers about 1.67% (0.143 M ha) of net cropped area (Table 1). The main reason for remaining fallow in the wet season of the cropping patterns is that the area remains under at least 50 cm stagnant water for about a month. Furthermore, the unavailability of higher yield potential semi-deep water-tolerant wet season rice cultivars is a reason for the remaining fallow of the area in the wet season as lower yield potential local cultivars (1-1.5 t ha^{-1}) is not profitable. On average about 1 M ha semi deep-water areas remain fallow in the wet season which is the potential for growing a rice crop in the wet season (Kabir *et al.*, 2018). It indicates that there is also a potential for inclusion of a rice crop in the wet season in the second and eleventh most dominant cropping pattern as BRRI has already developed semi deep-water cultivar BRRI dhan91 (3.5 t ha^{-1}), and there are some local cultivars that perform well under stagnant water condition. If we can bring about 50% of the total areas of the cropping patterns, consequently an additional 0.641 M ha of land will be under cultivation of deep-water rice, which can contribute an additional 1.57 million tons of rice to total rice production. The additional rice production was estimated for a 0.641 ha area with a 2.45 t ha^{-1} yield with a 30% yield gap for BRRI dhan91 in stress conditions.

Thirdly, fallow in the dry season followed by fallow in the early wet season and T. Aman in the wet season was the third most dominant cropping pattern, cover about 6% of the total net cropped area (0.509 M ha) (Table 1). This cropping pattern is mainly located in Madhupur and Barind Tract, tidal saline, and non-saline coastal zone and the Chittagong Hill Tracts. Similarly, it is reported that Fallow-Fallow-T. Aman was the dominant cropping pattern in the tidal non-saline ecosystem in the Barishal region (Ibrahim *et al.*, 2017). Besides, Fallow-Fallow-T. Aman and Fallow-Aus-T. Aman was the major cropping pattern in the Sylhet region (Muttaleb *et al.*, 2017). The area remains fallow in the dry to early wet season mainly because of the unavailability of freshwater for irrigation in crops in the dry season. Besides, salinity and unavailability of the seed of saline tolerant cultivars is also a practical barrier for cropping in the dry and early wet season in the coastal region. It can be noted that the development of surface water irrigation facilities through the re-excavation of canals in the non-saline Barishal region can create an opportunity for the inclusion of rice or non-rice crops in the dry season in the existing Fallow-Fallow-T. Aman cropping pattern. Besides, dredging some areas of the river for following freshwater water from the upstream river to the downstream river in the tidal saline ecosystem in the coastal region may create an opportunity for storing freshwater in the river for irrigation in Boro rice. Moreover, trapping freshwater in the canals through closing sluice gate or constructing earthen embankment between canals and rivers in early December could be used for Boro rice cultivation in coastal regions.

If it is possible to reserve adequate freshwater for irrigation through strong policy supports for developing the above-mentioned facilities it may be possible to bring 40% of the total area of the cropping pattern (Fallow-Fallow-T. Aman) under Boro rice cultivation (e.g., 0.2 million ha) through the adoption of BRRI developed saline tolerant (8-10 dS/m) rice cultivar BRRI dhan67. The extrapolated additional rice production for the inclusion of Boro rice in the 0.2 M ha with a 3.96 t ha^{-1} yield is about 0.80 million tons of rice. Similarly, it is reported that there was potential to include Boro and even the Aus rice in the Fallow-Fallow-T. Aman cropping pattern in the non-saline tidal and haor ecosystems if access to irrigation water is ensured (Ibrahim *et al.* 2017; Muttaleb *et al.* 2017). Furthermore, there was potential for introducing T. Aman rice in the Mustard-Boro-Fallow cropping patterns (Table 1). There was also potential for introducing deepwater rice in the wet season in the Boro-Fallow-Fallow cropping pattern. Similarly, there was potential for introducing Boro and Aus rice in the (i) Grasspea-Fallow-T. Aman, (ii) Maize-Fallow-T. Aman, (iii) Wheat-Fallow-T. Aman and (iv) Mungbean-Fallow-T. Aman cropping patterns (Table 1).

Fourthly, some of the arable areas remain fallow round the year as current fallow and culturable waste. Some areas remain fallow because of absentee farmers and some areas are newly developed in riverine Char land etc. It was observed that current fallow land will be 0.3 M ha and culturable waste will be 0.2 M ha in 2030 (Fig. 9).

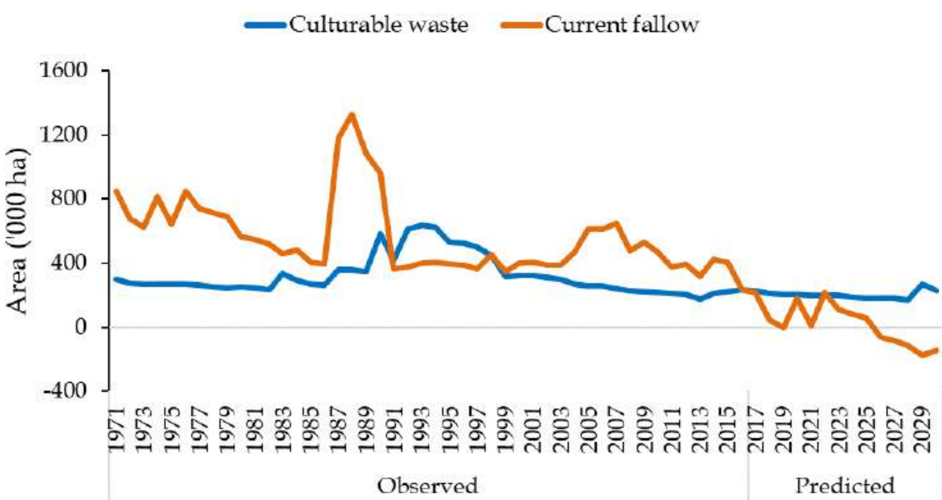

Fig. 9. Trend of culturable waste and current fallow during 1970-71 to 2030-31 in Bangladesh.

Similarly reported that there is an opportunity for enhancing rice production in the cultural wastelands in coastal Char lands in Barishal and Noakhali (Kabir *et al.,* 2020). If it is possible to bring 50% of these areas (0.25 M ha) under rice cultivation through providing appropriate technologies and extension supports we can add additional 0.99 million tons of rice in the total rice production with a 3.96 t ha^{-1} yield.

Fifthly, there is some marshy land such as Vabadaha and Bhutiar beel which mostly remains fallow round the year due to stagnant water because of inadequate drainage facilities. If it is possible to develop irrigation facilities through the excavation of canals, the area might come under Boro rice cropping. If we can bring 0.25 M ha under Boro rice cultivation, it can contribute 0.99 million tons to total rice production with a 3.96 t ha^{-1} yield.

Sixthly, the ethnic minorities in Chittagram Hill Tracts (CHT) grow crops by the hill agriculture (*jhum*) and plain land agriculture (plow agriculture). However, 22,413 *jhum* farmers are about 13% of total farm households in the CHT, most of them are not self-sufficient in rice production for their family subsistence for round the year. It was partly because of productivity of local cultivars Aus rice under the *jhum* system was low and partly because about 80% of the total 0.129 M ha arable land in the valley used only for rainfed rice cropping in the wet season. It can be noted that Fallow-Fallow-T. Aman is the second most dominant cropping pattern in CHT (Quais *et al.,* 2017). However, there is fresh surface water in the rivers, lakes, canals, and springs for irrigation as well as there is underground water for both shallow and deep aquifers irrigation in CHT. Besides, there is potential for reserving rainwater in the tank on the top of hills and excavating reservoirs or crick/cross dam or mini ponds for irrigation as more rainfall occurs in the CHT. Therefore, there is potential for increasing rice production by introducing Boro rice in 45% of the single T. Aman-based cropping pattern through developing infrastructure for irrigation (reservoirs and channels). Likewise, it is reported that there is an opportunity for enhancing rice production in the Chittagong Hill Tract (CHT) (Kabir *et al.,* 2020).

Besides, the fallow in the wet season followed by non-rice crops in the dry season and followed by Aus rice in the early wet season is the cropping system of 0.012 M ha *jhum* culture area in CHT and per hectare yield of Aus rice under *jhum* system was 1.20 t ha^{-1} (BRRI, 2019). Therefore, there is a potential for increasing 0.017 million tons production of Aus rice by (i) replacing local cultivars by the higher yield potential modern rice cultivators (3.5 t ha^{-1}) about 60% of total *jhum* culture area, and (ii) improving agronomic management.

Moreover, there is about 0.0136 M ha culturable waste land in Kaptai Lake at CHT. However, the area has potential for cropping rice and non-rice crops in the dry season (January- May) through rescheduling the time of opening sluice gates for drainage out the water from the Lake. Additional 0.0269 million tons of rice could be added to the national rice basket through introducing Boro rice in the 50% of the total culturable waste (0.0067 M ha) land of Kaptai lake subject to small intervention for (i) developing irrigation facilities and (ii) rescheduling the time of drainage out the lake water after harvesting Boro rice. These results indicate that increased total rice production not only will be played a vital role in increasing self-sufficiency in rice production at CHT but also will be contributed to improving livelihood through increasing farm income and generating employment opportunities for the wage workers.

Finally, there are some areas such as char land, mudflat and sandy beaches which are potential for cropping. These accreted lands have been increasing and will be increased in the future (Hasan *et. al.*, 2013). There are about 0.55 M ha accreted land which has the potential to contribute to the total rice production. However, some of the areas are not suitable for rice cropping and even there is no settlement in some areas as well. Therefore, it needs to shift people for the rice-growing period. If it is possible to bring 50% of the area (0.275 M ha) under local cultivars rice cultivation with 1.22 t ha^{-1} yield potential, it can contribute about 0.34-million-ton rice in the total production.

Research, development and extension activities for enhancing rice production

Table 2 presents a detailed research plan for increasing rice production through cropping in the fallow period and unutilized area. Mainly on-farm research trials are needed to conduct for identifying the potential for cropping system intensification in the appropriate domains. Besides, large-scale demonstrations are needed to set for boosting farmers' confidence about the potential of introducing rice in the fallow period and unexplored areas. Moreover, farmers' field days are required to arrange and broadcast the success story in the print and electronic media for informing the potential of farmers across the country.

Table 3 presents the target for enhancing rice area by introducing rice in the fallow period and the unexplored areas across future conditions. The research and up-scaling activities will be undertaken in different selected upazilas and districts sequentially. Thirty-five percent target of introducing rice in the fallow period and unexplored areas will be achieved by 2021-30. Thereafter, about 35% target of introducing rice in the fallow period and unexplored areas will be achieved by 2031-40. Finally, about 30% target of introducing rice in the fallow period and unexplored areas will be achieved by 2041-50.

Table 2. Research, development and extension activities for increasing rice production through cropping in fallow period and unutilized area.

Phase	Activity
Research and development	1. Site selection and characterization through baseline survey (PRA, FGD) and SWOT analysis.
	2. Scope validation trials for introducing rice in the existing cropping patterns (CP) and unutilized areas. The main aim of the activity is to identify problems and prospects of improving existing CPs. Demonstration trials will set on fields of the selected progressive farmers to achieve the goal.
	3. Lecture-based and hands-on training through demonstrations trial at farmers' fields will be provided to farmers and other stakeholders.
	4. Informing farmers about the potential of introducing rice in the existing CPs and unutilized areas through print and electronic media.
	5. Large-scale demonstrations will be set on farmers' fields and field days will be arranged to present the potential to mass farmers of nearby villages.
	6. The economic viability of cropping in the fallow period and on the unexplored areas will be assessed, and farmers' feedback will be gathered for future improvement.
Extension	7. Extension linkage will be developed for wide-scale dissemination of the research outcomes to farmers' fields through arranging workshops with DAE and policy people.
	8. The success story will be widely broadcasted in print and electronic media for motivating farmers and extension personnel.

Table 3. Targeted cropping patterns and areas for introducing rice in the fallow period and unexplored areas across future conditions.

Cropping pattern (CP)/Intervention/ Ecosystem	Area of ECP (ha)	Targeted area to introduce rice (ha)	Extrapolated production increase (MT)	Activities (Table 2)		
				2021-30	2031-40	2041-50
Cropping in fallow period of CP						
ECP: Boro-Fallow-T. Aman ICP: Boro-Aus-T. Aman	23,06,005	5,76,000	1.38	1-8	1-8	1-8
ECP1: Boro-Fallow-Fallow ECP2:Mustard-Boro-Fallow ICP1: Boro-Deepwater rice ICP2:Mustard-Boro-Deepwater rice	11,39,530 1,43,130	5,69,765 71,565	1.57	1-8	1-8	1-8
ECP:Fallow-Fallow-T. Aman ICP1: Fallow-Aus-T. Aman ICP2: Boro-Aus-T. Aman	5,09,480	2,03,792	0.80	1-8	1-8	1-8
ECP:Grasspea/Maize/Wheat/ Mungbean-Fallow-T. Aman ICP:Grasspea/Maize/Wheat/ Mungbean-Aus-T. Aman	3,00,520	97,542	0.29	1-8	1-8	1-8
Utilization of unexplored area						
Cultivable waste	200,000	100,000	0.40	1-8	1-8	1-8
Stagnant water area	250,000	62,500	0.25	1-8	1-8	1-8
Char land	550,000	275,000	0.34	1-8	1-8	1-8
Hilly area	43,210	23,102	0.061	1-8	1-8	1-8

CP: Cropping pattern, ICP: Improved cropping pattern, ECP: Existing cropping pattern

CONCLUSION

Sustainable intensification of rice cropping might be possible for meeting up food security challenges for the growing population in 2030 through the introduction of a rice crop in 2.211 M ha in the fallow period in the existing major cropping patterns and utilizing fallow land for rice cropping. About six million tons of additional rice can be added to total rice production through strengthening policy supports for implementing appropriate action plans to achieve the goals.

RECOMMENDATION

- Strategic policy support for developing must needed infrastructure for freshwater reserve and strengthening research for developing technologies is required for intensification of cropping through (i) transforming some major existing cropping patterns by utilizing the fallow period and (ii) utilizing the fallow lands for higher and sustainable growth in rice production.
- Suitable rice cultivars and component technologies are needed to be developed to fit into the existing major cropping pattern and disseminate in the unutilized land.
- Extension supports (training and large-scale demonstration) need to be strengthened for improving farmers' knowledge about component technologies through training and large-scale demonstration for adopting another rice crop in the fallow period and grow the crop in the unutilized land.
- The seed of suitable rice cultivars should be available at the farm level.
- Improvement in irrigation systems and excavation of silted up canals or rivers should be developed to expand the irrigated areas

- The fair price of paddy rice needs to be ensured to make the enterprise economically viable for motivating farmers for investing their time and money in cultivating an additional rice crop as most farmers are self-sufficient in rice production from the existing cropping pattern.

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AUTHORS' CONTRIBUTION

MN, AK, MUS and MSK generated idea; MUS, MARS and MAAM coordinated the research; MN, ABMM and MJK developed methodology; MN, AK, MJK, ABMM, MARS, MUS and MSK provided scientific insights; MN, AK, ABMM and MAAM gathered data, carried out analysis and synthesis; MN, AK, MJK and ABMM did the writings for all versions of the manuscript; MJK, MAAM, MARS and MUS 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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Risk of Rice Cultivation under Current and Future Environment and Market

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ABSTRACT

Risk is an inevitable feature of agriculture globally, and it might increase over time in the future. The study assesses the risk of rice cultivation in the three seasons under current and future conditions. The software programme @Risk version 7.6 was used to simulate the risk-return trade of rice cultivation in the three seasons in Bangladesh. The likelihood of having negative net income for the Aus (90%) and Boro (80%) rice was very high under the current market and environmental conditions. Besides, the chance of obtaining negative net income was notable for T. Aman (33%). Both the yield and price variation significantly contributed to the fluctuation of returns of rice production. However, with the current seasonal variation in yield, the probability of having negative net income for paddy rice was very low under the farmers' expected price (Aman: 22.5 BDT kg^{-1}, Boro: 25 BDT kg^{-1} and Aus: 24 BDT kg^{-1}). The result indicates that only access to the fair price of the rough rice can ensure the economic sustainability of the rice production. Likewise, chances of having a negative net income of paddy rice in 2030 will be zero under the extrapolated yield (Aman: 5.3 kg ha^{-1}, Boro: 6.3 kg ha^{-1} and Aus: 4.8 kg ha^{-1}) and price (Aman: 31.75 BDT kg^{-1}, Boro: 30.75 BDT kg^{-1} and Aus: 30 BDT kg^{-1}). The findings indicate that rice cultivation in the three seasons will be economically sustainable, subject to achieving the expected genetic gain and ensuring access to the projected price. Thus, policy supports are needed to ensure farmers' access to a fair price, improve management practice, and strengthen research to enhance genetic gain for sustainable rice farming under future conditions.

Key words: Production risk, market risk, yield and price fluctuations, economic sustainability.

INTRODUCTION

Bangladesh is geographically and geo-morphologically critically vulnerable to climate change and hot spots of catastrophic natural calamities. It was due mainly to the country located between two distinct environments, particularly the Bay of Bengal in the south and the Himalayas in the north. Besides, greater dependency on agriculture and overpopulation aggravates the susceptibility. Every year the country faces one or more natural calamities in the form of floods, droughts, tropical cyclones, storm surges, and coastal erosion. As a result, concede substantial economic and physical losses as well as a causality of human death (WB, 2013). Table 1 presents the physical vulnerability of different sectors to extreme events, including sea-level rise, floods, droughts and cyclones, and storm surges. It indicates that farming in Bangladesh operates under substantial production risk due to climatic vulnerability. Additionally, seasonal fluctuation in the price of rough rice at farm-gate also substantially affected the economic viability of rice cultivation in Bangladesh (Kabir *et al.*, 2017; Kabir *et al.*, 2019).

The risks sometimes jeopardize farm enterprises and force farmers to adapt to the conditions by adjusting their production and management strategies (Hardaker *et al.*, 2004; ADB, 2002; Duong *et al.*, 2019). The risk of T. Aman rice farming was higher for small farmers, followed by medium and large farmers in southwest coastal Bangladesh (Kabir, 2016). Similarly, Aus rice farming was riskier, followed by Boro rice and T. Aman rice (BRRI, 2016). Therefore, evaluation of farm enterprises or technologies solely in terms of average or expected return cannot reflect real scenarios without assessment of risk (Ullah et al., 2016). Besides, the accounting level of risk

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associated with farming is the key to formulating policies for the sustainability of risky farm decisions (Hardaker et al., 2004; Nastis et al., 2019). Moreover, the information about risk returns trade needs to account for planning at higher levels for the welfare of the farm families (Hardaker *et al*., 2004; Kabir *et al.*, 2019) as the country has to produce 44.6 MT of rice by 2050 for 215.4 million population of Bangladesh (Kabir *et al.*, 2015). Thus, this study focuses on assessing the risk of rice cultivation in the three rice growing seasons under current and future conditions.

Followed by the introduction, description of methods is presented briefly. It includes choosing a software programme and the assumption of the stochastic budgets to analyze the risk-return trade of Aus, T. Aman, and Boro rice. It presents results and discussions, including major sources of farming risks and their management strategies. This was followed by analyses of the economic viability (profitability and risks) of the Aus, T. Aman, and Boro rice under current and future conditions. Finally, conclusions are outlined.

METHODOLOGY

In particular, input use pattern, yield, and prices of inputs and outputs of Aus, T. Aman, and Boro rice, farm-level data were collected from 900 key informant rice farmers over the last three years (2017-2019). The data were collected from favourable and unfavourable ecosystems, including salinity, drought, submergence, and haor areas. Stochastic budgets were constructed for representative enterprise budgets to evaluate the riskiness of rice in the Aus, T. Aman, and Boro season. The software programme @RISK Version 7.6 was used along with Excel to derive cumulative density functions (CDFs) of gross margin (GM) and net income (NI) (PC, 2018). Monte Carlo simulation was run following triangular probability distributions of yield and price (Hardaker *et al.,* 2004). It was due to that distribution is best fitted with available data.

The model was run under the following three conditions:

- Farmers perceived seasonal variation in yield and price of Aus, T. Aman, and Boro rice for the last five years (Table 2);
- Farmers observed seasonal variation in rice yield over the last five years and their expected price of Aus, T. Aman and Boro rice (Table 2); and,

Table 1. Intensity of impacts on different sectors due to climate change in Bangladesh.

Sectorial vulnerability context	Physical vulnerability context							
	ET	Sea level rise		DT	Flood		Cyclone and storm surges	Erosion and accretion
		CI	SI		River flood	Flash flood		
Crop Agriculture	+++	++	+++	+++	+	++	+++	-
Fisheries	++	+	+	++	++	+	+	-
Livestock	++	++	+++	-	-	+	+++	-
Infrastructure	+	++	-	-	++	+	+	+++
Industries	++	+++	++	-	++	+	+	-
Biodiversity	++	+++	+++	-	++	-	+	-
Health	+++	+	+++	-	++	-	++	-
Settlement	-	-	-	-	-	-	+++	+++
Energy	++	+	-	-	+	-	+	-

Note: '+++' refers to high, '++' refers to moderate, '+' refers to low level of relationship, '-' refers not measure. ET: Extreme temperature, DT: Drought, CI: Coastal inundation, SI: Salinity intrusion.

Source: Adapted from MoEF (2005, p. 19).

- Extrapolated yield (1% genetic gain per year over existing yield with same seasonal variation and yield gap), price (6.5% annual increase as compound growth rate), and cost (15% increase from baseline cost) in 2030 (Table 2).

Although Monti-Carlo simulation software is highly potential to give precise predictions about risk-return trade-offs. However, the projection of paddy prices under future conditions based on the exponential growth coefficient is not highly reliable.

The best-case yield was obtained under favourable weather conditions and the worst-case yield under unfavourable weather conditions. However, the complete crop loss by extreme events such as floods, cyclones, and storm surges was excluded from the worst seasonal yields. With regards to price, the best price is the price that is obtained in some seasons, and the worst-case price is the price that is obtained in some seasons. The typical seasonal grain yield and paddy prices were the yield and paddy prices obtained in most cases. The highest number of iterations (10,000) was used for simulating each CDF as it increased the stability of the distribution (Lien, 2003). The analysis of risk involved comparing the CDFs of the alternative cropping options. Simple stochastic dominance rules were applied (Anderson *et al.*, 1988; Dillon and Hardaker, 1993).

Table 2 presents grain yield and price of Aus, T. Aman, and Boro rough rice across three scenarios under historical and 2030 conditions. The current yield was the farmers' observed best, normal, and worst seasonal yield. The current and expected prices were the farmers' observed and expected high, most likely, and low price of rice. Yield in different seasonal conditions was extrapolated by considering 1% genetic gain per year over existing yield with the same seasonal variation and yield gap. The best seasonal price was extrapolated through accounting for the annual exponential growth of the rough price for the last 22 years.

Table 2. Grain yield and price of Aus, T. Aman, and Boro rough rice in Bangladesh across three scenarios under historical and 2030 conditions.

Season	Parameter	Condition	Best seasonal/ high	Typical/ normal	Worst seasonal/ low
Aus	Grain yield ($t\ ha^{-1}$)	Current	5.60	4.80	3.50
		Extrapolated	6.20	5.30	4.10
	Price ($BDT\ kg^{-1}$)	Current	22.50	18.50	16.50
		Farmers expected	25.00	22.50	20.00
		Extrapolated	38.25	31.75	28.25
Aman	Grain yield ($t\ ha^{-1}$)	Current	6.50	5.70	4.40
		Extrapolated	7.30	6.30	5.20
	Price ($BDT\ kg^{-1}$)	Current	23.50	18.00	15.50
		Farmers expected	27.50	25.00	22.50
		Extrapolated	40.25	30.75	26.50
Boro	Grain yield ($t\ ha^{-1}$)	Current	6.50	5.70	4.40
		Extrapolated	7.30	6.30	5.20
	Price ($BDT\ kg^{-1}$)	Current	23.50	18.00	15.50
		Farmers expected	27.50	25.00	22.50
		Extrapolated	40.25	30.75	26.50

Note: Extrapolated indicates 2030 conditions

RESULTS AND DISCUSSION

Risk sources and management strategies

Risk is an inevitable feature of agriculture both in developed and developing countries as farming operates in uncertain biophysical and economic circumstances (Hardaker *et al.,* 2004; Moschini and Hennessy, 2001). The risk might increase over time under future conditions, including changes in climate and environment, social and economic phenomenon, and trade in agricultural products (Hardaker *et al.,* 2004; ADB, 2002; Duong *et al.*, 2019). The seasonal fluctuations of farm output because of weather variations and price variations, because of the influences of market stakeholders and government policy are the primary sources of risk faced by the farmers (Musser and Patrick, 2002). Figure 1 presents major risks and risk management strategies in farming. The production risk mainly concerns seasonal fluctuations of crop yield due to the unpredictable weather and the incidence of pests and diseases. Besides, the interaction of new technologies, farm characteristics, management practices, the quality of inputs, machinery efficiency, and breeds are also influenced by production risk (Musser and Patrick, 2002; Hardaker *et al.,* 2004; Kabir *et al*. 2020). The diversification, adoption of biotic and abiotic stress-tolerant cultivars, and pursuing precision agriculture, crop insurance, and contract production are the major production risk management strategies. Contract farming ensured access to favourable prices, insurance protection against loss, and diversification spread the risks (Musser and Patrick, 2002; Hardaker *et al.,* 2004; https://rnrinag. uwagec.org/).

Market risk concerns variations in inputs and outputs prices and quantities of marketable surplus. The changes in government policies (e.g., tariff, levy, and subsidy) or laws, unpredictable global markets for inputs and outputs, exchange rates, and variations in quantities supply due to weather are the drivers of market risk (Musser and Patrick, 2002; Hardaker *et al.,* 2004; Kabir *et al*. 2020). Developing a balanced approach or marketing plan based on available information and skills through forwarding, sequential, and contract marketing are major market risk management strategies. Besides, direct sales to consumers and vertical integration might reduce market risk (Musser and Patrick, 2002; Hardaker *et al.,* 2004; https://rnrinag. uwagec.org/).

Risk arises from changes in government rules that have far-reaching implications for farm production, and profitability is institutional or political risk. The major sources of institutional risk include unfavourable policy changes, failure to honor trade agreements by foreign governments, and dealing between business partners and other trading organizations (Hardaker *et al.*, 2004).

Economic viability under three scenarios of yield and price of rice

The economic viability of rice was estimated under three conditions:

- Current conditions indicate farmers' perceived seasonal variation in yield and price of rice over the last five years. The rice yield and price variations indicate the seasonal fluctuation of grain yield and paddy price because of seasonal variation in weather and market.
- Current environmental conditions and farmers expected price- similarly, farmers perceived seasonal variation in paddy yield across the last five years. Besides, farmers' expected price is the price that farmers expect currently to make profitable the rice enterprises.
- Extrapolated yield and price- extrapolated grain yield is the projected yield of rice in 2030 under expected genetic gain and better management. Besides, the extrapolated price is the projected price in 2030 based on the exponential growth rate of paddy prices over the last 18 years.

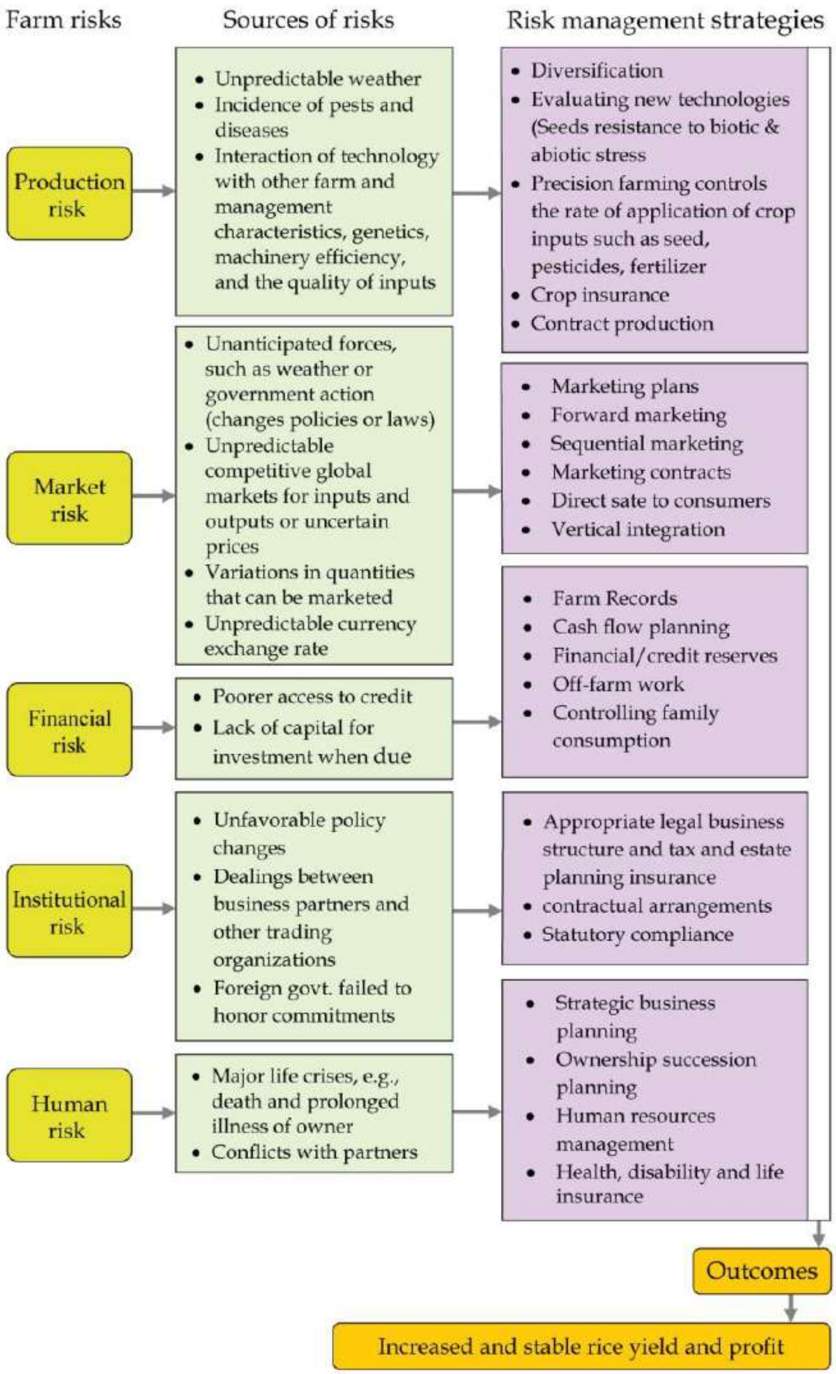

Fig. 1. Major risks and risk management strategies in farming.

Source: Musser and Patrick, 2002; Hardaker *et al*., 2004; https://rnrinag.uwagec.org/https://rnri nag.uwagec.org/

Risk of rice cultivation at current conditions

Figure 2 presents cumulative probability distribution functions (CDFs) of gross margin per hectare of Aus, T. Aman, and Boro rice at farmers' perceived seasonal variation in yield and price over the last five years.

The probability of having a positive gross margin of T. Aman in the current environment and market conditions was 100%. Under similar conditions, the chances of giving a positive gross margin for Aus was about 98% and decreased to 97% for Boro. The risk analysis results indicate that despite the current seasonal price and yield variations, farmers have higher chances of having a positive gross margin from rice irrespective of seasons. The CDF of T. Aman shows first-degree stochastic dominance over Boro and Aus rice, and the CDF of Boro shows second-degree stochastic dominance over Aus rice, indicating that T. Aman gave a higher gross margin followed by Boro and Aus (Fig. 2).

The sources of variability in the different measures of enterprise returns were analyzed using the @RISK software. In Figure 3, the total variation in gross margin per hectare is partitioned between the sources, namely, the seasonal variation in the yield and price of Aus, T. Aman, and Boro. The variation in the paddy yield contributed most to the gross margin of T. Aman and Aus, followed by fluctuation in price. On the contrary, price variation contributed most to variability in the gross margin of Boro rice, followed by grain yield (Fig. 3). However, the contribution of price in the variability in gross margin of T. Aman and Boro decreased notably (Fig. 4), subject to ensured access to farmers' expected price.

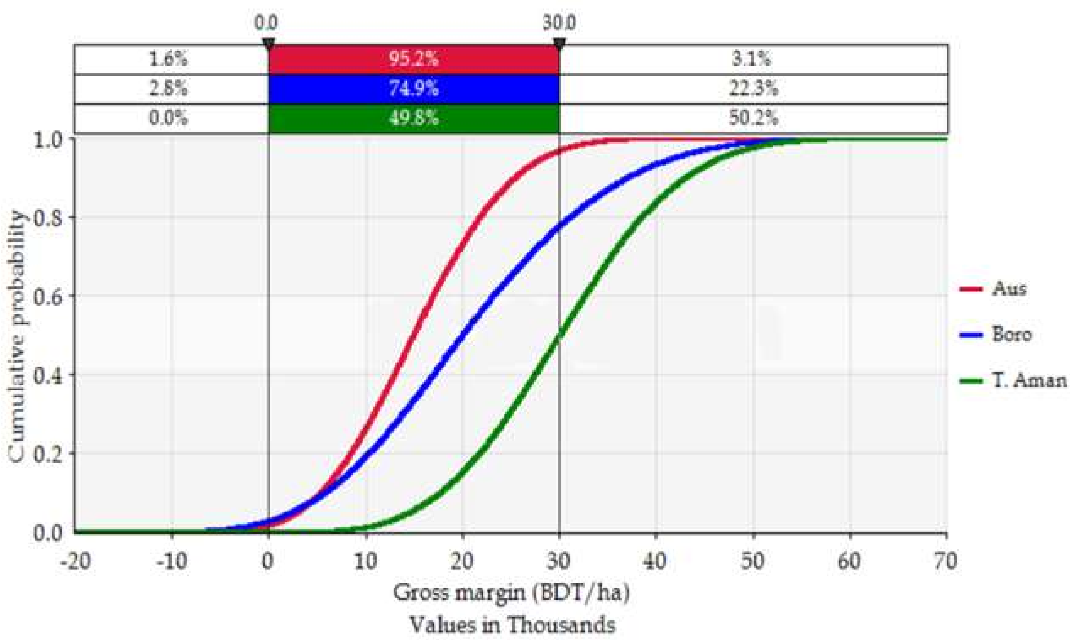

Fig. 2. Cumulative probability distribution of gross margin of Aus, T. Aman, and Boro rice in Bangladesh at farmers' perceived seasonal variation in yield and price.

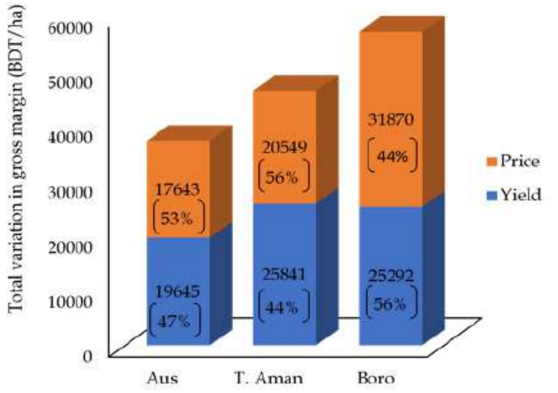

Fig. 3. Inputs ranked by an effect on gross margin per hectare of Aus, T. Aman, and Boro rice in Bangladesh at farmers' perceived seasonal variation in yield and price.

Note: Total variation in gross margin is consists of variation in gross margin due to variation in yield and price; Figures in the bracket indicate percent variation.

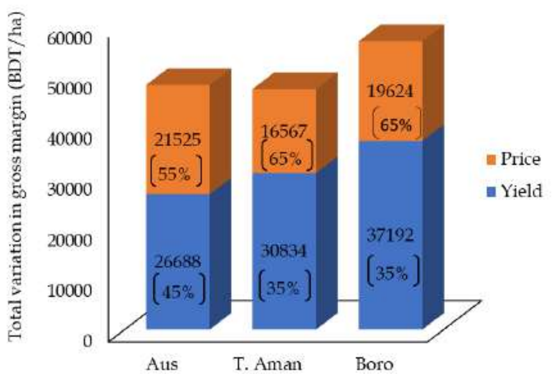

Fig. 4. Inputs ranked by the effect on gross margin per hectare of Aus, T. Aman, and Boro rice in Bangladesh at farmers' perceived seasonal variation in yield and expected price.

Note: Total variation in gross margin is consist of variation in gross margin due to variation in yield and price. Figures in the bracket indicate percent variation.

Figure 5 presents CDFs of net income per hectare of Aus, T. Aman, and Boro rice at farmers' perceived seasonal variation in yield and price. The CDF of T. Aman shows first-degree stochastic dominance over Boro and Aus rice. Besides, the CDF of Boro shows second-degree stochastic dominance over Aus rice. The results indicating that Aus is the most risker, followed by Boro and T. Aman. It can be seen that farmers have over 90% chance of having total loss from Aus rice. The probability of total loss decreased to 80% for Boro rice and 33% for T. Aman. The risk analysis results indicate that the likelihood of having negative net income for Aus and Boro rice was very high under the current market and environmental conditions. Besides, the risk for T. Aman farming was notable (Fig. 5).

Risk at current environmental conditions and farmers' expected price

Figure 6 presents CDFs of net income per hectare of Aus, T. Aman, and Boro rice at farmers' perceived seasonal variation in yield and expected price. CDFs show that despite seasonal variation in grain yield, the probability of having negative net income from Aus (7%), Boro (4%), and Aman (1%) decreased substantially at farmers' expected price. The key insight of the results of risk analysis is that farmers' ensuring access to fair prices is the cornerstone of the economic sustainability of rice production. It can be noted that farmers expected price is nearly consistent with the government procurement price. Thus, policy supports to ensure farmers' access to government declared price is critically important for sustainable rice production in Bangladesh.

Risk at extrapolated yield and price

Figure 7 presents the CDFs of net income per ha of Aus, T. Aman, and Boro rice at extrapolated yield, price, and cost in 2030. CDFs show that at extrapolated paddy yield and price, not only the likelihood of having a negative net income of rice was zero, but also the chances of giving net income per hectare over BDT 5,000 even for Aus rice was 100%. The probability of having net income per hectare over BDT 40,000 for Boro and T. Aman was in the range between 99-100% at extrapolated yield and price in 2030. It was also the case that even the chance of having net income per hectare over BDT 40,000 for Aus rice is about 58%. The results of risk analysis indicate that rice cultivation in the different seasons will be economically sustainable, subject to achieving the extrapolated genetic gain and ensuring access to the projected price in 2030.

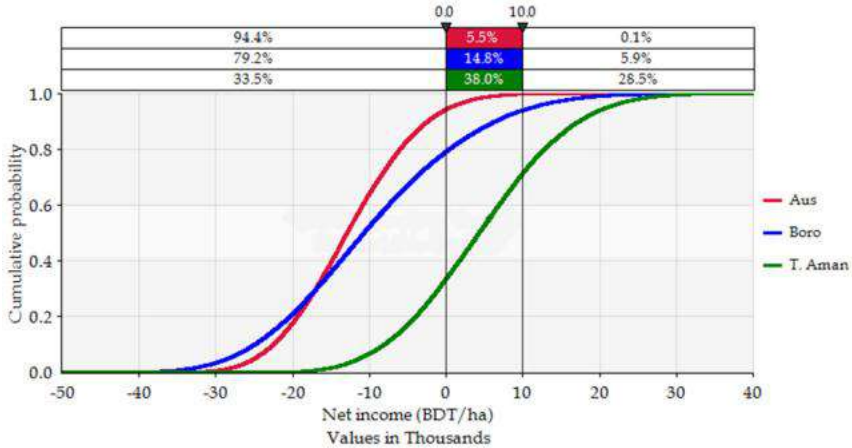

Fig. 5. Cumulative probability distribution of net income of Aus, T. Aman, and Boro rice in Bangladesh at farmers' perceived seasonal variation in yield and price.

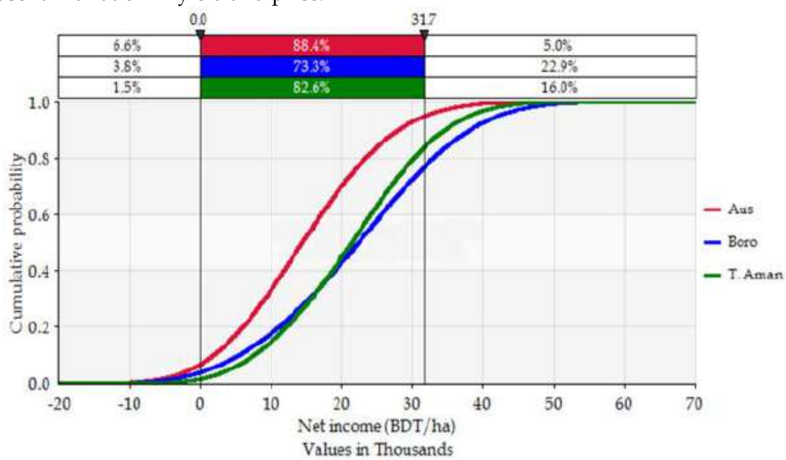

Fig. 6. Cumulative probability distribution of net income of Aus, T. Aman, and Boro rice in Bangladesh at farmers' perceived seasonal variation in yield and their expected price.

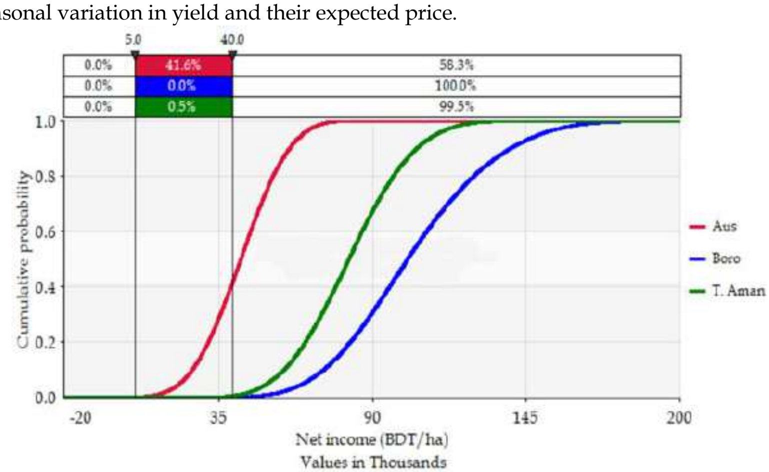

Fig. 7. The cumulative probability distribution of net income of Aus, T. Aman, and Boro rice in Bangladesh at extrapolated yield and price

CONCLUSION

The likelihood of having negative net income for the Aus (90%) and Boro (80%) rice was very high under the current market and environmental conditions. Besides, the chances of obtaining negative net income were notable for T. Aman (33%). Both the yield and price variation significantly contributed to the fluctuation of returns of rice production. However, with the current seasonal variation in yield, the probability of having negative net income for rough rice was very low under the farmers' expected price (Aman: 22.5 BDT kg^{-1}, Boro: 25 BDT kg^{-1}, and Aus: 24 BDT kg^{-1}). The finding indicates that only accessing the fair price of the rough rice can ensure the economic sustainability of the rice production. Likewise, chances of having a negative net income of paddy rice in 2030 will be zero under the extrapolated yield (Aman: 5.3 kg ha^{-1}, Boro: 6.3 kg ha^{-1} and Aus: 4.8 kg ha^{-1}) and price (Aman: 31.75 BDT kg^{-1}, Boro: 30.75 BDT kg^{-1} and Aus: 30 BDT kg^{-1}). The finding indicates that only ensuring access to the fair price of the rough rice is vital for the economic sustainability of rice production. Thus, policy supports are required for (i) controlling unscrupulous market deals, (ii) enhancing genetic gain, and (iii) improving management practice for sustainable rice farming under future conditions.

RECOMMENDATIONS

The following policy recommendations could help ensure a sustainable rice production system in Bangladesh.

- Research should be strengthened for developing higher yield potential stress-tolerant rice cultivars to alleviate the adverse consequences of harsher future environmental conditions.
- The extension programmes should be focused on the rapid dissemination of the newly developed higher yield potential cultivars to the end-users in the respective stress ecosystems and a favourable environment.
- The minimum fair price of grain quality-wise rough rice at farm-gate should be declared, and farmers' excess to the price should be ensured to alleviate market risk.
- Farmers' access to soft credit (low-interest rate) should be ensured to improve their adaptive capacity.
- Insurance schemes for rice farming should be commenced protecting farmers from the adverse consequences of extreme weather events (e.g., including droughts, floods, and cyclones).

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AUTHORS' CONTRIBUTION

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

DECLARATION OF INTERESTS

A version of the paper was published in the 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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Role of Training in Transferring Rice Production Technologies to Farm Level

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ABSTRACT

Farmers' knowledge gap in modern rice cultural practice is the main cause of the existing yield gap in Bangladesh. Thus, this paper delineates; (i) the level of farmers' knowledge gap; (ii) assesses the impact of training on changes in the farmers' skills, knowledge as well as technology adoption, and crop performance. Finally propose an approach for improving farmers' skills on modern rice cultural practices through fruitful training. Secondary data, in particular, journal articles were reviewed and analyzed in the paper. From the analysis, we found that majority of the farmers (85%) belong to the medium level of the overall knowledge gap category. There was a significant increase in the knowledge and skills of farmers after undertaking the training. As a result, the rice yield of trained progressive farmers increased to 4.7 t ha^{-1} in 2012 from 3.1 t ha^{-1} in 2008. However, the rice yield of ordinary trained farmers increased to 3.7 t ha^{-1} in 2012 from around 2.6 t ha^{-1} in 2008. The traditional extension approach was less efficacious to improve farmers' knowledge gap and disseminate the rice production technologies to the farm level. Therefore, strengthening BRRI's capacity to provide seed to seed training to most of the DAE personnel to upgrade their skills on modern rice technologies is critically important. Besides, demonstrations based farmers training might be highly productive in transferring modern rice production technologies to the farmers.

Key words: Farmers' knowledge gap, rice yield gap, seed to seed training, training approach

INTRODUCTION

Training is a mode of transferring knowledge and skills and has been applying in the age-long for improving performance and responsibilities of skills and unskilled man-power (Adisa and Okunade, 1995). Similarly, reported that it is a highly effective approach for updating farmers' knowledge and disseminating modern technologies to farmers' fields for raising crop productivity (Ajayi, 2015). Department of Agriculture Extension (DAE) a public organization in Bangladesh, is the main body to disseminate the modern technologies and information developed by research organizations to the farmers. Although, private sectors, NGOs, and research organizations also the other forces of the technology transfer process. DAE introduces farmers to modern technologies of rice and non-rice crops through training, technology demonstration, field days, etc, and provides information to farmers about modern technologies. However, there was about a 20% rice yield gap (Kabir *et al.,* 2015) and it is estimated as 20.68% (Kabir *et al.,* 2020) in Bangladesh. For reducing the yield gap, it is critically important to (i) disseminate the higher yield potential rice cultivars and component technologies to farmers' fields as well as (ii) improve farmers' knowledge about the production technologies. To do so, several diffusion determinants of new technologies are used in extension approaches which are mentioned earlier. Among the major diffusion determinants of new technologies, knowledge spillover is considered one of the most important factors in technology dissemination (Munshi, 2004; Foster *et al.*, 1985, Basely and Case, 1993).

Hence, training is considered one of the most effective tools to improve farmers' knowledge and skills in modern technologies.

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However, it was reported that most of the training programmes have so many weaknesses (Satter, 2012). As a result, it fails to upgrade farmers knowledge and skills up to the mark or desired level. Moreover, most of the DAE trainers have no training on modern rice cultural practices and agronomic management. Therefore, improvement of knowledge and skills of extension personnel and farmers on modern technologies of rice is required to disseminate the technologies to farmers' fields. Thus, the present study assessed(i) farmers' knowledge gap on the recommended practices of rice cultivation, (ii) the impact of training on the knowledge and adoption of technologies, and (iii) delineates a training model to reduce farmers' knowledge gap.

Followed by the introduction, it presents methodology, results and discussion, including farmers' knowledge gap on modern rice cultivation practices, the impact of training on knowledge and skills, and the impact of training on the adoption of technologies and yield. It is followed by current technology transfer approach and effectiveness of the BRRI training activities, a model for alleviating drawback of conventional training approach, training module and methods and future directions of BRRI training programme. This is followed by conclusions and recommendations.

METHODOLOGY

Relevant published journal articles were collected through google scholars and analyzed the key findings on the status of farmers' knowledge on modern cultural practices, the significance of training on farmers' skills, and the performance of rice crops. It indicates that mainly secondary data were used for the study. Besides, primary data on the significance of training and how to improve farmer's skills were collected through key informant's interviews with researchers and extension personnel.

RESULTS AND DISCUSSION

Impact of training: earlier experiences

Farmers knowledge gap on modern rice cultivation practices.

The data in Table 1 reveal that the majority of the rice farmers (85%) belonged to the medium knowledge gap category with a mean technological gap score of 56.51, followed by 15% of total respondents belong to the low knowledge gap category with a mean technological gap score of 21.94. It is also evident from the data that none of the rice farmers belongs to the high knowledge gap category.

It was observed that there was a wide variation in the farmer's knowledge gap when it was measured based on key yield contributing factors like pest management, fertilizer management, harvest and post harvest management etc. It can be noted that farmers have the highest knowledge gap on pest management followed by fertilizer management and, harvest as well as post-harvest management (Table 2).

Table 1. Classification of farmers based on knowledge gap.

Category	Frequency	Percent	Mean	SD
Low knowledge gap (Up to 33%)	15	15	21.94	14.12
Medium knowledge gap(34 to 84%)	85	85	56.51	16.96
High knowledge gap (85% and above)	0	0.00	00.00	0.00
Total	100	100	-	-

Note: The knowledge gap was measured based on the difference between the possible knowledge score for the 36 questions and the actual knowledge score, SD-Standard deviation. Source: *Tengli and Sharma, 2017, p.1227*

Table 2. Farmers' knowledge gap on different yield contributing factors.

Yield contributing factors	Knowledge gap	Rank
Variety and its attributes	151	6th
Seedling age	499	4th
Time of transplanting and spacing	470	5th
Pest management	900	1th
Fertilizer management	863	2th
Harvest and post-harvest management	734	3rd

Note: The knowledge gap of the farmers is classified based on six yield contributing factors. It was estimated by deducting the obtained knowledge score from the possible knowledge score of the respondents under each factor. Adopted from *Islam et al., 2018, p.3*

Impact of training on knowledge and skills

Table 3 presents the rating of farmers' knowledge and skills on major yield contributing factors before and after undertaking training. Overall, positive changes have taken place in the farmer's skills on all the production techniques after training. The positive changes have taken place on farmers' knowledge on major yield contributing factors including variety, seedling age, time of transplanting and spacing, pest management, fertilizer management, harvest, and post-harvest management, and irrigation as well as water management.

Impact of training on the adoption of technologies and yield

Table 4 presents rice yield and level of adoption of major yield contributing factors by farm types from 2008 to 2012. It was observed that progressive farmers obtained a slightly higher yield (0.5 t ha^{-1}) even before the training in 2008. Besides, there was no statistically significant yield difference between intermediary and ordinary farmers. However, per hectare rice yield of progressive farmers after training increased to 4.4 t ha^{-1} in 2009 from 3.1 t ha^{-1} in 2008 due to higher adoption of technologies. The adoption rate of modern technologies increased substantially since 2009 and continued to increase until 2012. As a result, progressive farmers obtained a significantly higher yield (2 t ha^{-1}) than ordinary farmers from 2009 to 2011.

Table 3. Changes of knowledge and skills after the training.

Yield contributing aspect	Knowledge (mean)				Skill acquired (mean)			
	Before training	After training	Mean diff	Z value	Before training	After training	Mean diff	Z value
Variety and its attributes	2.68	4.06	1.38	1.68	1.68	4.10	2.42	3.21
Seedling age	2.98	3.96	0.98	1.13	2.07	3.87	1.80	3.43
Time of transplanting and spacing	1.67	3.00	1.33	1.62	2.06	4.21	2.15	4.46
Pest management	1.38	3.87	2.49	2.00	1.40	3.53	2.13	1.74
Fertilizer management	2.80	3.11	0.31	1.13	2.53	3.43	0.90	3.03
Harvest and post-harvest management	1.86	2.70	0.84	0.32	-	-	-	-
Irrigation and water management	1.92	3.17	1.25	1.86	-	-	-	-

Note: Modified from *Aphunu and Ajayi, 2010, p.135.*Pre and post-test were done before and after training for each participant. Z-test was used to test the significant difference between knowledge and skills possessed before and after the training programme.

Table 4. Rice yield and adoption of technologies by different farmers' types.

Year and sample size	Progressive farmer					
	Yield (tha^{-1})	Fertilizer ($kgha^{-1}$)	% of used modern varieties	% of plots with improved bund	% of leveled plots	%farmers transplanted in rows
2008 (n=13)	3.1*	63.4	46.2*	15.4**	46.2	23.1
2009(n=13)	4.4***	115.8***	69.2***	23.1***	76.9	76.9***
2010(n=16)	4.8***	137.7***	65.8***	31.3***	81.3	93.8***
2011(n=14)	5.3***	164.5***	54.8***	42.9***	85.7	92.9***
2012(n=13)	4.7**	131.3***	66.7***	15.4	76.9	92.3***
	Moderately progressive farmer					
2008 (n=23)	2.5	22.2**	30.4	13.0*	43.5**	13
2009(n=27)	2.6	49	44.4**	18.5***	70.4	44.4***
2010(n=31)	2.8	79.1	40.8**	22.6***	74.2	64.5***
2011(n=24)	4.6***	103.9*	34.4	33.3**	79.2	45.8**
2012(n=24)	3.9	95.2	49.5**	33.3***	62.5	58.3**
	Ordinary farmer					
2008 (n=135)	2.6	46.5	26.7	3	54.8	11.1
2009 (n=142)	2.7	58.3	26.8	4.9	64.1	19
2010 (n=155)	2.5	69.7	25.7	7.7	69	25.8
2011 (n=130)	3.6	85.8	23.6	16.2	76.2	26.9
2012 (n=130)	3.7	83.2	32.9	11.5	66.9	36.9

Source: Adopted from Yuko Nakano *et al.* 2018, p. 25. Note: *, ** and *** indicate level of significance at the 1%, 5% and 10% level

As soon as after receiving training in 2009, intermediary farmers also improved their rice production practices through adopting modern cultural practices. Which resulted to get them increased yield (4.6 t ha^{-1}) in 2011 compared to 2008 (2.5 t ha^{-1}). It was observed that the rate of rice yield increased for intermediary farmers was lower than progressive farmers, and rice yield difference between ordinary and intermediary farmers was only significant in 2011.

From the above discussion, it can be claimed that an effective mode of training is highly efficacious to increase farmers' knowledge and skills; consequently, farm productivity might increase because of the rising adoption of modern technologies and improving agronomic management.

Current Technology Transfer Approach

The public and private sectors, including NGOs, research organizations as well as farmers play a pivotal role to transfer technologies and knowledge to the end-users for enhancing the production of agriculture crops, livestock, and aquaculture. DAE has been contributing most to disseminating technologies to the farmers' fields as it is mainly mandated to disseminate the modern agriculture technologies and information to the farmers' field through training and others extension methods. Figure 1 presents the approaches of disseminating the National Agriculture Research System (NARS) developed modern agricultural technologies through DAE. It was observed that NARS organizations developed higher yield potential cultivars and component technologies for agronomic, biotic, and abiotic stress management of crops. Thereafter, the NARS organizations provide training on modern cultural practices to extension and other development personnel for disseminating the technologies to farmers' fields. In this process of disseminating technologies to the farm level, the upazila level and field level (i.e., Sub Assistant Agriculture Officer) agriculture extension personnel play a vital role to make the farmers adopt the technology. Therefore, they need to acquire the latest technical information innovated by the research organizations. So that they can perform their job effectively.

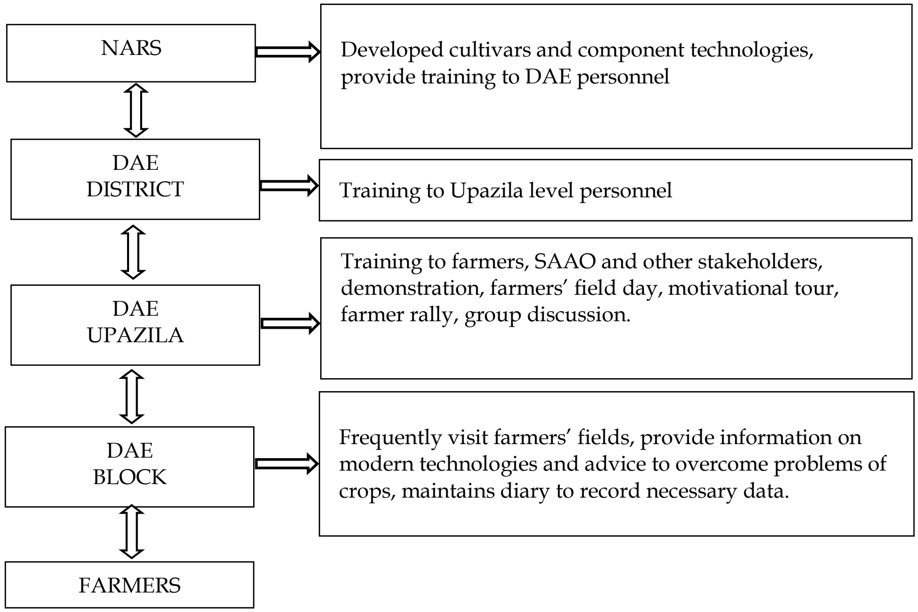

Fig. 1. Information flow during technology dissemination of DAE (Adopted from Satter, 2012).Note: Department of Agriculture Extension (DAE), National Agriculture Research System (NARS), Sub-assistant Agriculture officer (SAAO)

BRRI is not only a pioneer in developing higher yield potential rice cultivars and component technologies but also provides short and long-term training to DAE personnel disseminating the cultivars and technologies to farm level. The trainees may contribute directly through providing training to farmers and indirectly through providing training to trainers for disseminating the technologies for enhancing rice production. In total, BRRI has given training to 34,332 extension personnel since its establishment.

Effectiveness of the BRRI training

As mentioned above that BRRI has given training to 34,332 extension personnel since its establishment. Table 5 presents the performance of trainees trained by BRRI. It was observed that the mean score of pre-evaluation of extension personnel on modern rice cultural practice was 26%, indicating that there was about a three-fourths gap in their knowledge on rice technologies. However, the mean post-evaluation score of the trainees was 76%, indicating that the knowledge gap reduced to one-fourth from three-fourths. It was also the case that the post-evaluation score of 95% of total trainees was 86, which implies that the training provided by BRRI was highly potential to improve trainees' knowledge. In short, results of the quantitative evaluation suggest the training programme was highly successful and well-received by the participants.

Table 5. Distribution of respondents according to their knowledge scores.

Category	Pre training			Post training		
	Trainee (%)	Score	Mean score	Trainee (%)	Score	Mean score
Low knowledge (<60)	98	28		0	0	
Medium knowledge(60-79)	2	61	26	5	76	76
High knowledge (> 80)	0	0		95	86	
Total	100			100		

Note: Achievement was measured from difference between mean of post-training and mean of pre-training.

Despite such joint effort of NARS and DAE, still, there is over 20% of rice yield gap in Bangladesh (Kabir *et. al.*, 2015). Which is one of the key barrier on the way to achieving the food security challenges for 2030.

Now the question is, why the yield gap occurs? Firstly, farmers are not being able to adopt modern cultural management practices. Because with an exception to a few, training provided to farmers on rice productions neither demand-driven nor its curricula are modern and consistent with farmers' needs. Besides, it is a one-way deliberation in a classroom by the speaker, so that farmers usually have few scopes for participation. Furthermore, the same farmers are invited for most training, and some of them are not solely farmers (farming is their secondary occupation) so that they are not fully concentrated on the talk and subject matters of the training (Satter, 2012). Secondly, there is a gap in the adoption of recommended management practices, consequently, about 15% of yield loss has occurred because of poor agronomic management (Kabir *et al*., 2020).

Model for alleviating drawback of conventional training approach

Figure 2 presents a new model to improve farmers' knowledge through alleviating the limitations of the conventional farmers' training method. The model delineates the roles of each collaborator and impacts the models on farmers' performance, rice yield, income, and livelihoods.

Roles of different collaborators

BRRI Training Division is a vital collaborator to provide training to the DAE personnel. BRRI should provide training to upazila level extension personnel to develop master trainers on rice production, and they will serve as master trainers to provide training to field level extension personnel and progressive farmers. Upazila level DAE personnel are one of the key collaborators; every upazila level agriculture office should be the main center of resources for disseminating technologies to farmers through training and other technology disseminating methods.

The field-level agriculture extension personnel i.e., SAAO is responsible for identifying the local need for training and selecting farmers through discussion with the key informant farmers including village leaders, imam of the mosque, and school teachers. The school teachers and fertilizer traders will also be invited to the training with progressive farmers. The upazila level extension personnel will provide training to farmers. There will be a training evaluation team that will monitor and assess the training programme as an independent third party looking to verify the effectiveness of the training programme.

Training module and methods

A rice production training module needs to be developed. It will cover a wide range of topics including rice variety and seed, agronomic management, pest management, fertilizer and irrigation management, post-harvest technology, and safe use of agrochemicals.

A group of 15-20 farmers consisting of an adult male and female member irrespective of farm size will be selected. The progressive farmers, school teachers, seed, and fertilizer traders also are trained as some farmers frequently ask for suggestions on fertilizers and pesticide application in rice crops from them.

Secondly, the DAE personnel will go to the village for providing training, and the training will be arranged at the farm household. It will be an informal training with two-way deliberation through question and answer. In addition to the lecture, some demonstrations will be set in the farmers' fields to provide hands-on training to the selected farm family members. The trained farmers will be encouraged to share knowledge with the neighbouring farmers and relatives in the community.

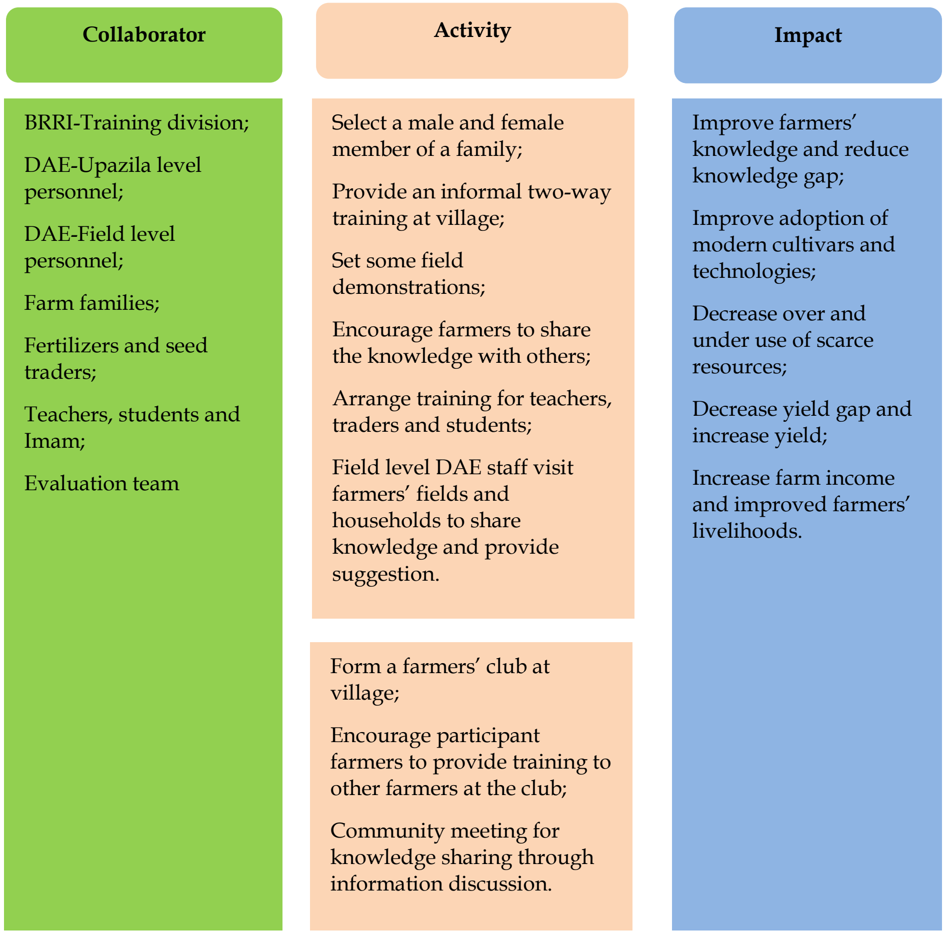

Fig. 2. Propose farmers training models (Developed based on *Croplife Int. Aisbl, 2013*).

Thirdly, a farmers' club will be constructed in each village under the core programme of government consisting of all farmers where trained farmers will meet with non-training farmers to share acquired knowledge to improve community performance.

Finally, the master trainers will give a lecture to students in the village level secondary school and *madrasa* (religious school) to improve their knowledge on modern rice production technologies as most of the students came from the farm families and participated in the farming activities.

Impact of training module

Both the participant and non-participant farmers' knowledge gap will be reduced after such a compressive approach of training at the village level. As a result, the adoption of modern technologies including cultivars, agronomic management, pest and water management will be increased. Not only the judicious use of scarce resources (land, labor, water, seeds, fertilizers, and pesticides) will be ensured but also the performance of the rice crop will be improved. Besides, the yield gap will be decreased, and farmers' livelihood will be improved because of increasing income due to increased yield and decreased cost for the judicious application of resources.

BRRI training programme: Future directions

Table 6 presents anticipated training needs for disseminating rice technologies to farmers' fields in Bangladesh until 2050. Firstly, the training aims to develop the knowladge and skills of entry and mid-level rice researchers to harvest their full potential in the development and dissemination of rice technologies. Secondly, the proposed training is aimed to update the knowledge and skills of field-level extension personnel including Sub-assistant Agriculture Officer (SAAO), Agriculture Extension Officer (AEO), and Additional Agriculture Officer (AAO) to disseminating the knowledge to root level farmers. The focus of the training is to develop master trainers on modern rice production practices to provide training to farmers. It can be noted that farmers' knowledge and skills on major yield contributing factors of rice have positively changed after training (Table 3). Besides, per hectare rice yield of progressive farmers increased to 4.4 t ha^{-1} in 2009 from 3.1 t ha^{-1} in 2008 after training. Similarly, in case of intermediary farmers it increased to 4.6 t ha^{-1} in 2011 from 2.5 t ha^{-1} in 2008 after training (Table 4). The results indicate that training has a substantial impact to reduce farmers' knowledge gap, consequently reduced the yield gap. Besides, BRRI Training Division has been set a target to provide an adequate number of skilled researchers and extension personnel to address the goal.

Table 6. Training for disseminating rice technologies to farmers' field under future conditions in Bangladesh.

Aim	Training theme /title	Participant	Duration (week)	Year		
				2021-2030	2031-2040	2041-2050
Capacity buildup	Modern rice production	Scientist	8	120	150	200
	Molecular technology		8	150	200	200
	Writing journal articles		1	500	500	500
	Bioinformatics		1	120	120	120
	Communication skill		1	200	230	250
	Research methodology		1	400	400	400
	Writing PP		1	400	400	400
Capacity buildup	Modern rice production and data collection methods	SA	1	120	120	120
Technology dissemination	Modern rice production	AEO/ AAO	4	1,200	1,200	1,200
	Rice pest, agronomic & irrigation management		1	1,500	1,500	1,500
	Hybrid seed production		1	1,500	1,500	1,500
Technology dissemination	Modern rice production	SAAO	1	7,000	8,000	10,000
	Farmers' fields day	Farmers/ Traders/ Teacher/ Imam	0.7	80,000	100,000	120,000
Updating policy level	Cutting edge BRRI technology appraisal	Senior management	0.7	5	5	5

SA= Scientific Assistant, PP=Project Proposal, Senior Management-Public and Private Organization

CONCLUSION

Farmers' lack of knowledge is the main reason for high yield gap in Bangladesh, despite strenuous efforts of public and private sectors including NGOs. Training facilitates improve farmers' knowledge and skills, signaficantly and increased adoption of recommended technologies, consequently increased yield and farm income. However, the conventional approach of training has some limitations to improve farmers' knowledge up to the mark. Therefore, a model is proposed to provide effective training to farmers through the collaboration of researcher, extension, and community level. Besides, capacity of the Training Division and BRRI scientists needs to be strengthened to provide seed to seed rice production training to the DAE personnel for upgrading their capacity on modern rice technologies. Moreover, demonstration-based farmers' training might be highly productive in transferring modern rice production technologies to the farmers. Finally, policy supports are needed for implementing proposed future directions of training needs for dissemination of rice technologies to the farmers' fields.

RECOMMENDATIONS

The policy supports are essential for strengthening (i) BRRI's capacity to provide hands-on training to most of the DAE's personnel for enhancing their skills on modern rice production practice and (ii) DAE capacity to provide whole family seed to seed rice production training through technology demonstration at farmers' fields in each DAE block to alleviate farmers' knowledge gap for achieving the full potential of the rice cultivars for sustainable rice production.

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AUTHORS' CONTRIBUTION

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

DECLARATION OF INTERESTS

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