Progress and Challenges of Wheat Production in the Era of Climate Change: A Bangladesh Perspective

Naresh Chandra Deb Barma, Akbar Hossain, Md. Abdul Hakim, Khondoker Abdul Mottaleb, Md. Ashraful Alam, Md. Mostafa Ali Reza, and Md. Motiar Rohman

Contents

Abstract In Bangladesh after rice, wheat is considered the second most important staple cereal. Although Bangladesh is one of the principal rice-consuming countries with per capita consumption of rice 171 kg year^{-1}, the consumption of wheat in Bangladesh has intensely increased over the years. From the year 1961 to 2013, the annual per capita wheat intake in Bangladesh has increased by 102% from 8.62 to 17.47 kg. Currently, Bangladesh mostly relies on import to meet surging demand. During 2011–2013, triennium average, Bangladesh imported 2.86 million tons of

---

N. C. D. Barma · A. Hossain (✉) · Md. A. Hakim · Md. A. Alam · Md. M. A. Reza
Bangladesh Wheat and Maize Research Institute (BWMRI), Rajshahi, Bangladesh

K. A. Mottaleb
Socioeconomics Program (SEP), International Maize and Wheat Improvement Center (CIMMYT), Texcoco, México

Md. M. Rohman (✉)
Plant Breeding Division, Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh

M. Hasanuzzaman et al. (eds.), *Wheat Production in Changing Environments*,
https://doi.org/10.1007/978-981-13-6883-7_24

wheat worth of USD 957.4 million. During 2018 only, about 7.0 million tons of wheat has been imported, which is nearly 80% of the total wheat supplied in the country consisting of domestic production and import. It is anticipated that wheat intake will be further increased in Bangladesh in the future, due to the changes in lifestyle which stems from an increase in income and speedy urbanization. It is therefore imperative to supply more wheat in Bangladesh in the future to ensure food demand of growing population in Bangladesh. At the same time, sustainable wheat production in Bangladesh is threatened by several stresses (biotic and abiotic) in addition to the competition of wheat with other winter crops. The chapter has highlighted the major constraints and prospects of wheat cultivation in relation to possible improved technologies under changing climate and provided an up-to-date and comprehensive information on the wheat research of Bangladesh in relation to global warming. This chapter will thus allow wheat researchers to make a comprehensive new breeding and management programs in Bangladesh to mitigate future global warming, especially for recently emerged wheat blast disease in Bangladesh including South Asia.

Keywords Abiotic stress · Biotic stress · Bangladesh · Changing climate · Wheat

1 Introduction

The three major staple crops, wheat (*Triticum aestivum* L.), maize (*Zea mays*), and rice (*Oryza sativa*), are the fundamental blocks of food security in the world. These three major bowls of cereal supply 50% of the dietary energy to humanity (FAO 2018a). Among the three major staple crops, wheat is the most cultivated crop in the world and was domesticated around 10,000 years before (Eckardt 2010). For example, in 2016, wheat was cultivated at least in 124 countries on 220.1 million ha of land (FAO 2018b). In contrast, maize and rice were cultivated in 169 and 119 countries and on 187.9 and 159.8 million ha of land, respectively (FAO 2018b). In 2016, with an average wheat yield 3.4 t ha^{-1}, total wheat production in the globe was 749.5 million metric ton (MMT) (FAO 2018b). In the same year, rice and maize yields were 4.63 t ha^{-1} and 5.64 t ha^{-1}, respectively, and total rice and maize production were 740.9 MMT and 1060.1MMT, respectively.

Globally, wheat is cultivated in various agroclimatic zones ranging from the hot and humid area in Bangladesh in South Asia to extreme cold areas such as Kazakhstan and Canada. Based on biotic and abiotic stresses, rainfall, humidity, temperature, and major requirements for crop establishment, the global wheat area has been divided into 12 mega-environments (ME) (Fig. 1, Wheat Atlas 2016). Bangladesh, in South Asia, along with Paraguay in South America and parts of Nigeria and Sudan in Africa is located in ME 5 (Fig. 1). The ME 5 is characterized by high tropical rainfall; high humidity and the minimum temperature range between 11 °C and 16 °C, and wheat are sown in autumn. The major stresses in ME 5 are heat stress, spot blotch, and leaf and stem rust (Wheat Atlas 2016). Although wheat blast was

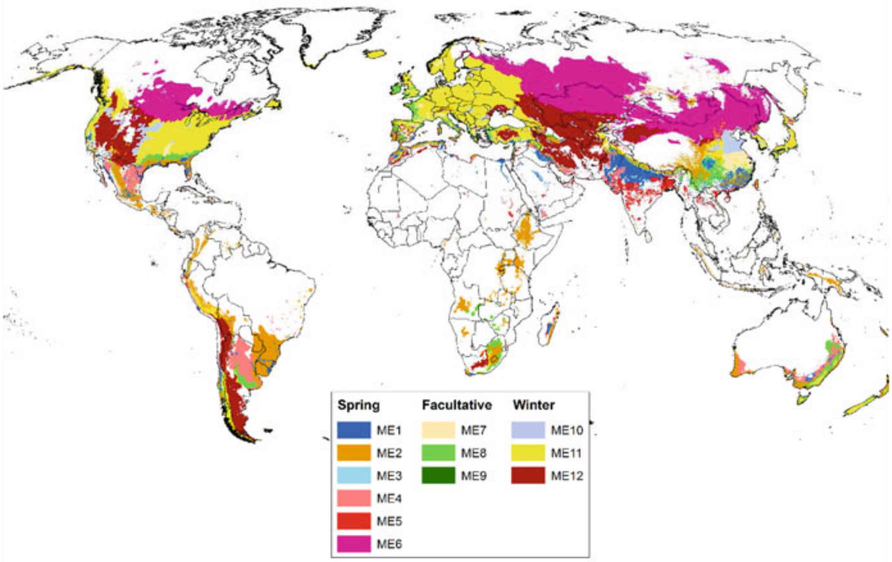

Fig. 1 Global map of wheat mega-environments based on Braun et al. (2010). Curtsey: Dr. Kai Sonder, Head, GIS, International Maize and Wheat Improvement Center (CIMMYT), Mexico

originally confined in Latin America (Malaker et al. 2016; Islam et al. 2016), in the year 2016, for the first time in the history, wheat blast has emerged in Bangladesh (ME 5). Wheat blast-induced yield loss in Bangladesh was recorded at 5% in the affected field of Bhola District to 51% in the affected field of Jhenaidah District (Islam et al. 2016).

Globally, wheat consumption ranges between yearly per capita 1.89 kg in Laos and 222.4 kg in Azerbaijan with per capita yearly average consumption 70.9 kg in 175 countries in the world (FAO 2018b). However, globally the average yearly per capita wheat consumption has increased by more than 19% from 54.9 kg to 65.4 kg from 1961 to 2013 (FAO 2018b). Interestingly, the rate of increase in wheat consumption is much higher in the poverty-stricken sub-Saharan African countries (Mason et al. 2015) and in the traditional rice-growing countries of South and Southeast Asia (Mottaleb et al. 2018a). For example, in Kenya, during 1961 to 2013, the yearly per capita wheat consumption increased by 356% from 7.6 kg to 34.7 kg, in Zambia increased by 38.6% from 7.4 kg to 12.1 kg, and in Zimbabwe by 49.3% from nearly 21 kg to 31.3 kg in the same period (FAO 2018b). In Asia, the yearly per capita wheat consumption has also been increasing in the traditional rice-producing and rice-consuming countries, such as in India and Indonesia. For example, in India from 1961 to 2013, the yearly per capita wheat consumption has increased by 117%, and at the same time in Indonesia, the yearly per capita wheat consumption had increased by 1442% (FAO 2018b).

With yearly per capita rice consumption of 171.7 kg, Bangladesh is one of the largest rice- producing and rice-consuming countries in the world (FAO 2018b). However, like many other sub-Saharan African and East and South Asian countries, wheat consumption in Bangladesh has been increasing significantly over the years (Mottaleb et al. 2018a, b). In 1963, the yearly per capita wheat consumption in Bangladesh was less than 11 kg that supplied daily 94 kcal per person (FAO 2018b). However, in 2013, the yearly per capita wheat consumption has increased at 17.5 kg, which is 59.4% more than the consumption level in 1963, and, currently, wheat supplies daily 150 kcal per capita (FAO 2018b).

With nearly 160 million population, Bangladesh is a rapidly emerging economy in South Asia. Since 2000, the GDP of Bangladesh, on average, has increased by 3.8–7.1% per annum (World Bank 2018a, b). As a result, the per capita nominal GDP of Bangladesh has increased from $363 in 2000 to $1516 in 2017 (World Bank 2018a, b). The US Department of Agriculture (2015) projected that the GDP of Bangladesh would increase by more than 6% per annum during 2018–2030. The urbanization process in Bangladesh is also rapid. In 2001, nearly 20% of the total 134 million population of Bangladesh was living in urban areas, whereas in 2018 nearly 36% of more than 160 million population of Bangladesh is currently living in urban areas (World Bank 2017a). Considering the medium fertility rate, it is projected that by 2050, the total population of Bangladesh will be 202 million (UN 2015), 56% of which is projected to reside in the urban areas (World Bank 2017b). The rapid economic growth, speedy urbanization, and the allied changes in lifestyle are responsible for the increased consumption of wheat in Bangladesh (e.g., Barker et al. 1985; Hossain 1998; Pingali 2007; Mottaleb et al. 2018b). It is expected that the faster economic growth and speedy urbanization process may further increase the wheat demand in Bangladesh in the future.

Worryingly, due to the population pressure, resources such as the per capita internally renewable freshwater (cubic meters) and the arable land (per capita/ha) in Bangladesh have been declining over the years. For example, the renewable internal freshwater per capita in 1971 was 1553.3 cubic meters, and the arable land was 0.1 ha per capita. In contrast, in 2014, the renewable internal freshwater per capita was reduced at 658.7 cubic meters, and the per capita arable land reduced at 0.05 ha (World Bank 2018a, b). It indicates additional wheat has to be produced from less land and water to meet the ever-growing demand; Bangladesh will rely more on import. In addition to declining resources, the change in global climate can also play significantly negative impacts on wheat and other cereal production in Bangladesh (IPCC 2007).

In Bangladesh, despite the yield growth, the total domestic wheat production remains more or less static due to the gradual decrease in wheat area (BBS 2018). Currently, the domestic production can only meet around 20% of the total wheat consumption of the country (USDA 2018; Barma 2018), and the demand-supply gap is met by import. In 1972, wheat was grown in only 0.13 million ha with a production of 0.11 million metric ton (MMT) (Hossain and Teixeira da Silva 2013). With the strong initiative of the government, wheat area gradually rose to its highest pick of 0.85 million ha with record production of 1.9 MMT. The wheat area in Bangladesh, however, started declining due to competition with other *rabi* crops, such as hybrid maize, and the area currently reduced to 0.42 million ha in

2017 with a production of 1.3 MMT with record wheat productivity of 3.13 t ha^{-1} (BBS 2018). However, out of total wheat consumption of 7.1 MMT in 2016–2017 in Bangladesh, wheat import contributed more than 80% (BBS 2018). Considering market volatility and the growing importance of wheat in Bangladesh's diet, a complete dependency on import cannot be a sustainable option.

This chapter examines the progress and challenges of wheat production in Bangladesh considering the increasing demand for wheat in light of the changing climate. This chapter is organized as follows. Section 2 elaborates the importance of wheat as a food grain in the world as well as Bangladesh. Section 3 presents scenario of wheat production at the global scale under changing climate. Section 4 presents historical background with purposes and objectives for wheat production in Bangladesh. Section 5 includes current trends of areas and production of wheat in Bangladesh. Section 6 presents the development of wheat varieties under changing climate. Section 7 presents constraints of wheat production in Bangladesh focusing on abiotic and biotic stresses and social constraints. Section 8 presents breeding and biotechnological approaches to improve stress tolerance wheat in Bangladesh. Section 9 presents research advances through agronomic practices for enhancing sustainable wheat production. Section 10 includes research progress on grain quality of wheat. Section 11 presents international linkages, collaboration, and policy issues for wheat production in Bangladesh; and finally Sect. 12 includes conclusion and policy implications.

2 Importance of Wheat as a Food Grain in the World as Well as Bangladesh

In human history, the domestication of wheat was a major landmark as it contributed to the transformation of the hunter-gatherer and nomadic primitive society to a more established agrarian society (Eckardt 2010). Since its domestication around 10,000 years ago, the crop became a major source of food grain in the world. With the increase in population, wheat cultivation was expanded dramatically across countries. In 1961, wheat was cultivated on 204.2 million ha of land in at least 94 countries, whereas in 2016, wheat was cultivated at least in 124 countries on 220.1 million ha of land (FAO 2018b). With yearly per capita current consumption of wheat 65.4 kg globally, wheat supplies on average per capita daily 527 kcal dietary energy, 15.9 grams protein and 2.43 grams fat (Table 1). Interestingly, over the years the yearly per capita wheat consumption in Europe and Oceania has been declining, whereas the yearly per capita wheat consumption in Africa, Americas and South America, Asia, and South Asia and Bangladesh has been increasing. In particular, the rate of increase in wheat consumption in Africa, Asia, and South Asia is higher compared to other regions (Table 1).

Table 1 Wheat as food in the world and selected regions of the world and Bangladesh

Region	World	Africa	Americas	South America	Europe	Oceania	Asia	South Asia	Bangladesh
Food supply quantity: kg/capita/year									
1963	55.4	29.6	57.0	52.0	131.3	96.9	30.2	36.0	11.0
1973	59.0	36.2	57.2	53.6	120.6	81.5	43.2	54.0	32.4
1983	67.5	45.8	61.1	58.8	114.4	77.3	59.6	59.9	27.2
1993	69.9	47.5	62.5	53.6	106.8	70.6	67.7	66.7	17.6
2003	66.8	46.7	63.2	57.2	108.7	71.6	63.7	65.7	21.3
2013	65.4	47.7	61.4	57.1	109.0	70.8	62.9	67.6	17.5
Food supply: kcal/capita/day									
1963	420	234	414	388	952	759	248	304	94
1973	458	285	418	399	875	635	360	457	276
1983	537	361	443	430	842	599	504	506	232
1993	562	374	456	397	806	552	567	558	150
2003	540	369	469	440	820	577	537	550	182
2013	527	376	459	429	827	579	524	566	150

Adapted from FAO (2018b)

Among the South Asian countries, the wheat consumption has dramatically increased in India (Rao 2000; Gandhi et al. 2004; Pingali 2007; Kumar et al. 2007; Mittal 2007; Deaton and Dreze 2009) and Bangladesh (Timsina et al. 2018; Mottaleb et al. 2018a, b, c). Using Bangladesh Household Income and Expenditure Survey data, Mottaleb et al. (2018a, b) demonstrate that the increased wheat consumption in Bangladesh is positively linked with the urbanization and the level of education and economic affluence of the households. It means economically affluent and urban households and households headed by educated heads and spouses consume more wheat than others. The increasing wheat consumption phenomenon in Asia and India, in particular, is termed as the westernization of Asian diets (Pingali 2007). Bangladesh and other South Asian countries, such as India and Nepal are economically emerging, and wheat is going to play a more important role in the South Asian diet in the future.

Even though with per capita rice consumption yearly 171 kg Bangladesh is the largest rice-consuming country in the world, the consumption of wheat has increased by 102% from 8.62 to 17.47 kg during 1961 to 2013 (Index Mundi 2018). Currently, Bangladesh mostly relies on import to meet surging demand due to the increasing consumer demand and also decreasing production (Index Mundi 2018; Figs. 2 and 3). During 2011–2013, triennium average, Bangladesh imported 2.86 million tons of wheat worth of USD 957.4 million (FAO 2018a). During 2018 only, about 7.0 million metric tons of grain has been imported (Index Mundi 2018) which is nearly 80% of the total wheat supplied in the country consisting of domestic production and import. With the changes in lifestyle which stems from an increase in income and speedy urbanization, it is projected that wheat consumption will further increase in Bangladesh in the future.

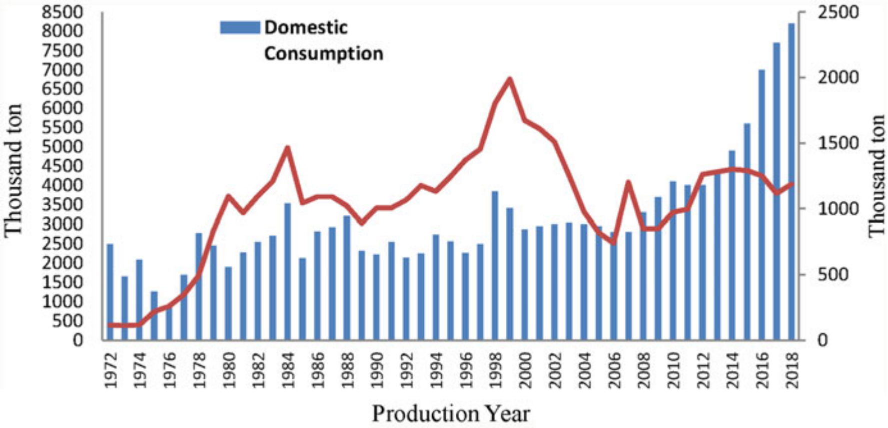

Fig. 2 Domestic consumption and production of wheat in 1000 ton, 1972–1918. (Data source: Index Mundi 2018; Barma 2018)

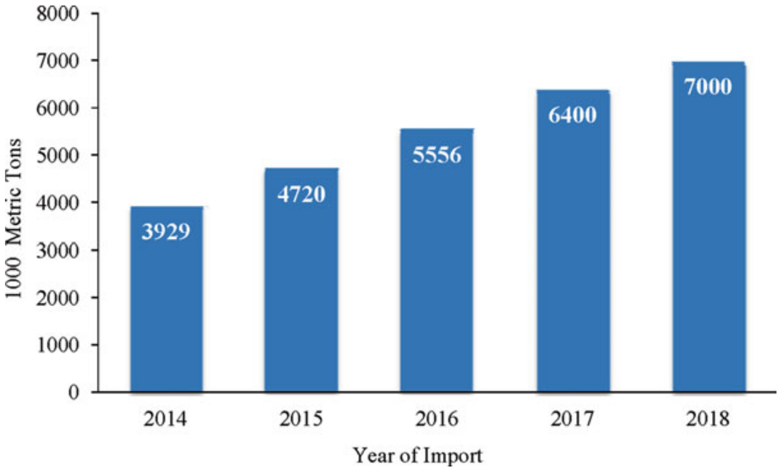

Fig. 3 Last 5-year import of wheat grain, 2014–2018 (1000′ MT). (Data source: Index Mundi 2018; Barma 2018)

3 Historical Background with Purposes and Objectives for Wheat Production in Bangladesh

Compared to rice, the major staple crop of Bangladesh, wheat is relatively a new crop in this country. The first initiative of wheat research in Bengal province was documented in 1936 (Ahmed and Meisner 1996). The notorious famine in 1943 in Bengal province that killed more than 3 million poor people from starvation and malnutrition (e.g., Sen 1981) forced the British Raj to strengthen wheat production in Bangladesh (the Bengal province) as an additional winter crop to ensure food security. Until 1955, *Gangajali* and *Jamali* were two local wheat varieties farmers produced sporadically (Ahmed and Meisner 1996).

During Pakistan period (1947–1971), government adopted some efforts to introduce wheat as an alternative winter crop realizing that rice alone could not meet food requirement of the ever-growing population of the country (Sarker et al. 2011). During 1955–1960, IP-52 and IP-125 wheat varieties developed by the Imperial Institute of Agricultural Research, New Delhi, were released in Bangladesh (Ahmed and Meisner 1996). The breakthrough, in research, however, came in 1965, when two Mexican high-yielding wheat varieties Sonora 64 and Penjamo 62 were tested in the northern part of Bangladesh and found promising (Ahmed and Meisner 1996; Hossain and Teixeira da Silva 2012). However, despite the spectacular performance of “Sonora 64” and “Penjamo 62” varieties, wheat was continuously treated as a nontraditional crop until the 1980s (Sarker et al. 2011). This was mainly because of the rapid expansion of the dry season irrigated *boro* rice, which emerged as the major competing crop of wheat. As rice is the staple food, the expansion of irrigated high-yielding modern *boro* rice in the dry season significantly outweighs wheat production in Bangladesh by increasing the net profitability of producing *boro* rice than any other winter crops including wheat (Morris et al. 1997). Consequently, wheat production in Bangladesh did not expand until recently. The nonavailability of the good-quality wheat seeds was another prominent problem on the expansion of wheat cultivation in Bangladesh during that time (e.g., Ahmed and Meisner 1996).

In 1965 and 1968, the head wheat breeder of CIMMYT visited Pakistan and convinced the national government that even without disturbing major crop production such as rice, it is possible to produce wheat on more than 1.5 million hectares of land in East Pakistan (Bangladesh) (Borlaug 1970; Byerlee and Siddiq 1994). During the same period, a massive program for producing high-yielding wheat in West Pakistan was already underway under active government support. After independence in 1971, the government emphasized the expansion of rice cultivation to ensure food security in the country while giving less importance to wheat at the beginning (Ahmed and Meisner 1996). Attitude toward wheat production, however, changed by a visit of the chief breeder and top scientists of CIMMYT in Bangladesh in 1974. The CIMMYT scientists successfully convinced Bangladesh government the country needs to diversify crop production to reduce climate-related risks in food production. As seed availability was the major problem, in 1975, the government imported 4000 tons of Sonalika and Kalyansona wheat seed from India and Mexico (Hossain and Teixeira da Silva 2013). The national government also trained the agriculture extension officers ahead of the wheat season. Ahmed and Meisner (1996) explained that this was the first major, well-organized, and successful government intervention to expand wheat production in Bangladesh.

4 Trend Areas, Production, and National Average Yield of Wheat in Bangladesh

Wheat is the important cereal next to rice in Bangladesh, which plays an important role in attaining food and nutritional security. In Bangladesh, the area of wheat in the year 1998–1999 was 0.85 million hectares (ha), and the production in the same year was 1.9 million ton (BBS 2011; WRC 2018), which was about 18 times more over the production of 1970–1971 and double the production of 1980–1981. The remarkable success in wheat production in the country was due to development of high-yielding and stress-tolerant wheat varieties with improved production technologies and also dissemination of these technologies to the farmers' field within a short period (Ahmed and Meisner 1996; Hossain and Teixeira da Silva 2013). However, in the previous year (in 1999), both area and production of wheat started to decrease mostly (area and production were 0.350 million ha and 1.30 m ton, respectively which is almost half of 1999) (BBS 2011), due to crop competition with maize, potato, *boro* rice, and vegetables and also lack of adaptation of good varieties as well as dissemination of improved management practices. However, the productivity has been increased significantly from 2.0 t ha^{-1} (1900) to 3.13 t ha^{-1} in 2016–2017 due to the introduction of heat-tolerant high-yielding wheat varieties and adoption of

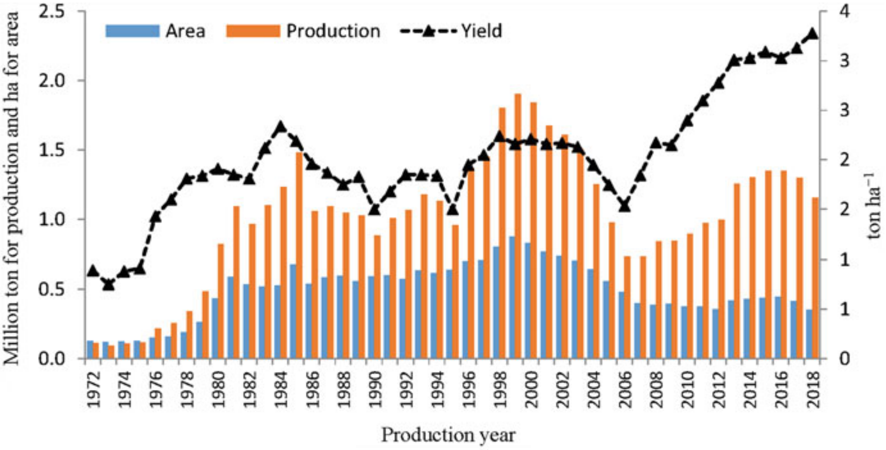

Fig. 4 Trend of area, production, and national average yield of wheat from 1972 to 2018. (Data source: Index Mundi 2018; Barma 2018)

wheat production technologies and dissemination of those to the farmers' field (Fig. 4). While, with an increase in disposable income, households tend to consume more high value-added food (Mottaleb et al. 2018a, b), wheat consumption in Bangladesh has been increasing every year, due to rapid dietary changes which are evident from the increase of import from 33.54 million metric ton in 2013 to 70.0 million metric ton in 2018 (Index Mundi 2018). During 2017–2018, 1.153 million tons of wheat was produced from 0.350 million ha that can meet only 20% of the national requirement (WRC 2018). On the other hand, the demand of wheat has been increasing every year at the rate of 13% due to rapid changes in dietary habit, socioeconomic upliftment, enhancement of per capita income, the rapid growth of fast food restaurant, the establishment of branded bakery and biscuit industries, etc. Due to the decrease in wheat area by 15% than the previous year, wheat production also reduced to about 12%. However, there is a significant increase in wheat productivity of 3.28 t ha^{-1} which was possible through the dissemination of high-yielding, disease-resistant, and stress-tolerant varieties and improved management practices to the farmers (Barma 2018; WRC 2018).

5 Development of Wheat Varieties Under Changing Climate

Wheat Research Centre (WRC) of BARI is entrusted to the research works for the improvement of wheat in Bangladesh and already released 33 high-yielding stress-tolerant varieties for commercial cultivation (Table 2). The recently released varieties are moderately tolerant to abiotic stresses such as terminal heat stress, drought, and salinity and also resistant/tolerant to major foliar diseases. Varieties released

Table 2 Cross and pedigree of released wheat varieties in Bangladesh

SL.	Variety name	Pedigree	Year of release	Average yield (t ha^{-1})
1	Sonora 64	YT 54/N10B//2*Y 54	1968	3.1
		II 8469-2Y-6C-6Y-4C-2Y-1C-0 MEX		
2	Kalyansona	PJ/GB 55, II 8156	1968	3.1
3	Inia 66	LR 64/SON 64	1972	3.2
		II 19008-83 M-100Y-100 M-100Y-100C		
4	Norteno 67	LR 64/SON 64	1972	3.5
		II 19008-52 M-4Y-3 M-2Y-OBGD (CIMMYT, Mexico)		
5	Sonalika	1154–388/AN/3/YT54/N1OB/LR64	1973	2.9
		II 18427-4R-1 M		
6	Tanori 71	SON 64/CNOREC//INIA 66	1974	3.7
		II 25717-4Y-3 M-1Y-0 M-0 MEX		
7	Nuri	Not available	1974	3.1
8	Jupateco 73	II 12300//LR 64/8156/3/NOR	1974	3.7
		II 30842-31R-2 M-2Y-0 M-0 MEX		
9	Balaka	PI'S′/HD 845	1979	3.3
		HD 1981-100JA-0I		
10	Doel	SON 64/KL REND//23,584	1979	3.0
		II 26592-8Y-2 M-2Y-0 M-0I		
11	Pavon 76	VCM//CNO/7C/3/KAL/BB	1979	3.7
		CM 8399-D-4 M-3Y-1 M-IY-IM-0Y-0BGD		
12	Ananda	KAL/BB	1983	2.8
		CM 26992-30 M-300Y-300 M-500 M-OY-OJA		
13	Kanchan	UP301/C306	1983	3.6
		1187–1-1P-5P-5JO-0JO		
14	Akbar	RON/TOB 'S'	1983	3.4
		CM 7705-3 M-1Y-2 M-2Y-OY-OJO		
15	Barkat	JUN'S′	1983	3.0
		CM 33483-C-7 M		
16	Aghrani	INIA/3/SON 64/P416OE//SON 64	1987	3.1
		PK 6841-2A-1A-OA		
17	Sawgat	IAS58/3/KAL/BB/2/ALD 'S'/4/OLN/TRM//ALD 'S'	1993	3.2
		CM 69201-B-1Y-3 M-7Y-1 M-OY		
18	Protiva	KU Head Selection	1993	3.3
19	BARI Gom 19 (Sourav)	NAC/VEE (NL 560)	1998	4.0
		CM 64224-5Y-1 M-1Y-2 M-0Y		
20	BARI Gom 20 (Gourab)	TURACO/CHIL	1998	4.1
		CM 92354-33 M-0Y-0 M-6Y-0B		
21	BARI Gom 21 (Shatabdi)	MRNG/BVC//BLO/PVN/3/PJB-81	2000	4.3
		CM98472-1JO-0JO-0JO-1JO-0JO-0R2DI		

(continued)

Table 2 (continued)

SL.	Variety name	Pedigree	Year of release	Average yield (t ha^{-1})
22	BARI Gom 22 (Sufi)	KAN/6/COQ/F61.70//CNDR/3/OLN/4/PHO/5/MRNG/ALDAN//CNO BD (JE) 349-X-0JE-9DI-10HR	2005	4.3
23	BARI Gom 23 (Bijoy)	NL297*2/LR25	2005	4.7
24	BARI Gom 24 (Prodip)	G. 162/BL 1316//NL 297	2005	4.7
25	BARI Gom 25	ZSH 12/HLB 19//2*NL297	2010	4.3
26	BARI Gom 26	ICTAL 123/3/RAWAL 87//VEE/HD 2285 BD(JO)9585-0JO-3JE-0JE-0JE-HRDI-RC5DI	2010	4.3
27	BARI Gom 27	WAXWING*2/VIVISTI CGSS01BOOO56T-099Y-099 M-099 M-099Y-099 M-14Y-0B	2012	4.6
28	BARI Gom 28	CHIL/2*STAR/4/BOW/CROW//BUC/PVN/3/2*VEE#10 CMSS95Y00624S-0100Y-0200 M-17Y-010 M-5Y-0 M	2012	4.8
29	BARI Gom 29	SOURAV/7/KLAT/SOREN//PSN/3/BOW/4/VEE#5. 10/5/CNO 67/MFD//MON/3/SERI/6/NL297 BD(DI)112S-0DI-030DI-030DI-030DI-9DI	2014	4.8
30	BARI Gom 30	BAW 677 (PASTOR/3/VEE#5//DOVE/BUC)/Bijoy BD(JA)1365S-0DI-15DI-3DI-HR12R3DI	2014	4.8
31	BARI Gom 31	KAL/BB/YD/3/PASTOR CMSS99M00981S-0P0M-040SY-040 M-040SY-16 M-0ZTY-0 M	2017	4.8
32	BARI Gom 32	SHATABDI/GOURAB BD(DI)1686S-0DI-1DI-0DI-0DI-3DI	2017	4.8
33	BARI Gom 33	KACHU/SOLALA CMSS09Y00580S-099Y-38 M-0WGY-4B-0Y	2017	4.8

Data source: Barma (2018)

since 2000 are high yielding and are mostly grown in the field, and percent coverage of released wheat varieties in the field is given in Fig. 5. Most of the released varieties are also early in maturity with their average yield of 3.1 to 4.8 t ha^{-1}. Year-wise released varieties and their yield ranges are also presented in Table 3. Among the latest popular 12 elite wheat varieties developed since 2000, 11 were found resistant against leaf rust (except “BARI Gom 24” (“Prodip”), and 3 varieties such as “BARI Gom 26,” “BARI Gom 27,” and “BARI Gom 29” were found resistant to stem rust (Ug99 race). “BARI Gom 21” (“Shatabdi”), “BARI Gom 30,” and “BARI Gom 32” were found tolerant against wheat blast (WB), whereas

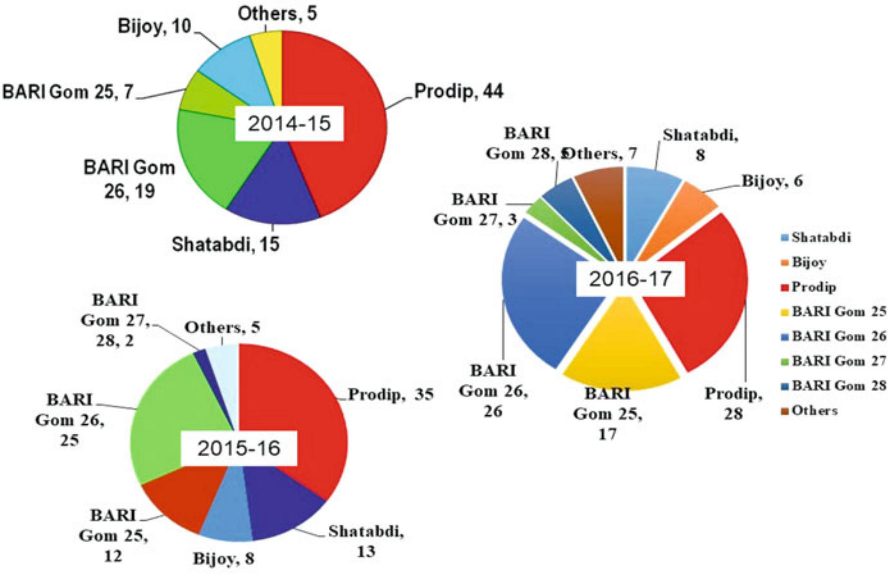

Fig. 5 Varietal coverage (%) in all over the country in the last 3 years (2014 to 2017). (Data source: Barma 2018)

Table 3 List of wheat varieties so far released by WRC, BARI since independent (1970)

SL#	Year of release	Number of varieties released	Yield range (t ha^{-1})
1	1970–1979	11	2.6–3.6
2	1980–1989	5	3.3–4.0
3	1990–1999	4	3.3–4.8
4	2000–2009	4	3.6–5.1
5	2010–2014	6	4.0–5.5
6	2015–2017	3	4.5–5.5

Data source: Barma (2018)

"BARI Gom 33" was found resistant against WB. Another two varieties such as "BARI Gom 28" and "BARI Gom 29" were found moderately susceptible against wheat blast (WB) (Table 4).

6 Constraints of Wheat Production in Bangladesh

6.1 Abiotic Stresses

Based on biotic and abiotic stresses, rainfall, humidity, temperature, and major requirements for crop establishment, the global wheat area has been divided into

Table 4 Percent coverage of existing elite wheat varieties and reaction to rust diseases

SL no.	Name of major varieties	Year of release	Coverage (%)	Reaction to diseases		
				LR	SR Ug99 race)	WB
1	BARI Gom 21 (Shatabdi)	2000	8	R	–	TOL
2	BARI Gom 23 (Bijoy)	2005	6	R	–	S
3	BARI Gom 24 (Prodip)	2005	28	S	–	S
4	BARI Gom 25	2010	17	R	–	S
5	BARI Gom 26	2010	26	R	R	S
6	BARI Gom 27	2012	3	R	R	S
7	BARI Gom 28	2012	5	R	–	MS
8	BARI Gom 29	2014	0.4	R	R	MS
9	BARI Gom 30	2014	0.6	R	–	TOL
10	BARI Gom 31	2017	–	R	–	S
11	BARI Gom 32	2017	–	R	–	TOL
12	BARI Gom 33	2017	–	R	–	R

Data source: Barma (2018)
LR leaf rust; *SR* (Ug99 race), stem rust, *WB* wheat blast, *R* resistance, *S* susceptible, *MS* moderately susceptible, *TOL* tolerance

12 mega-environments (ME) (Fig. 1, Wheat Atlas 2016). Bangladesh, in South Asia, along with Paraguay in South America and parts of Nigeria and Sudan in Africa is located in ME 5 (Fig. 1). The ME 5 is characterized by high tropical rainfall, high humidity, and the minimum temperature range between 11 and 16 °C, and wheat is sown in autumn (Wheat Atlas 2016). Bangladesh is located between the Himalayas and the Bay of Bengal; the country is very prone to natural disasters (World Bank 2009). Due to one of the most climate-vulnerable countries in the world, climate change accelerates the intensity and frequency of salinity, drought, high-temperature stress, flash floods, etc.

There are two ways to mitigate stresses in wheat, either by developing and practicing improved heat stress management practices or by developing and using tolerant cultivars against specific stress (Farooq et al. 2011). Modern wheat varieties are not sufficiently tolerant against stress and are susceptible to extreme abiotic stresses (Hussain et al. 2016). Therefore, developing cultivars tolerant to heat stress and other abiotic stresses is challenging for wheat breeders in Bangladesh (Hossain and Teixeira da Silva 2013). Considering the burning issues, scientists in WRC of BARI are trying to develop wheat varieties which are suitable to cultivate under abiotic stress conditions to meet the food security of increasing population.

A detailed description for the development of wheat varieties against abiotic stresses under changing climate is presented in Sect. 7.1.

6.2 *Biotic Constraints Especially Diseases*

Bangladesh, in South Asia, along with Paraguay in South America and parts of Nigeria and Sudan in Africa is located in ME 5 (Fig. 1), which is characterized by high tropical rainfall, high humidity, and the minimum temperature range between 11 °C and 16 °C. As a result, the area is highly vulnerable to major diseases such as spot blotch and leaf and stem rust (Wheat Atlas 2016).

Among them, *Bipolaris* leaf blight (spot blotch) caused by *Bipolaris sorokiniana* (Sacc.) Shoemaker is most important. The disease occurs every year in all wheat-growing areas of the country with varying degrees of severity depending on cultivar, sowing time, and location.

The second most important disease is leaf rust caused by *Puccinia triticina* Eriks. The disease usually appears in mid-February under the agroclimatic condition of Bangladesh. It may cause severe yield losses if a susceptible variety is late sown and infection occurs early in the crop season. The popular variety "Prodip" has become susceptible to leaf rust and may be seriously affected under late-sown condition. Stem rust caused by *P. graminis* Pers. f. sp. *tritici* Eriks. & Henn. was observed in 2014 and 2015 in the rust trap nurseries after three decades, but no Ug99 detected. Yellow rust caused by *P. striiformis* West. f. sp. *tritici* Eriks. & Henn. occurs occasionally with low to moderate severity. So far none of the rusts have reached an epidemic level in Bangladesh, but damaging epidemics may occur, particularly if a new virulent race develops or is introduced. Other diseases of regular occurrence are seedling blight caused by *B. sorokiniana*, foot and root rot caused by *Sclerotium rolfsii* Sacc., head blight caused by *B. sorokiniana*, and black point incited mainly by *B. sorokiniana* and *Alternaria alternata* (Fr.) Keiss. However, head blight and black point were quite frequent in 2017–2018. Powdery mildew caused by *Erysiphe graminis* f. sp. *tritici* has been observed since 2012 in late February with sporadic infection, though the disease was also noticed as sporadic in the 2017–2018 crop cycle.

A detailed description for the development of wheat varieties against different diseases under changing climate is presented in Sect. 7.2.

6.2.1 Wheat Blast: A New Threat on Food Security of Increasing Population

Although wheat blast (WB) caused by the fungus *Magnaporthe oryzae* pathotype *Triticum* (MoT) was most confined in Latin America (Malaker et al. 2016; Callaway 2016; Islam et al. 2016), in the year 2016, for the first time in the history, WB disease has been reported in Bangladesh (ME 5), which affected nearly 15,000 ha (3.5% of the total 0.43 million ha of wheat area in Bangladesh), with wheat yields in the affected fields reduced by 5–51% (Islam et al. 2016).

The disease also reappeared in 2017 and 2018 with comparatively low disease severity, and about 5–10% and 1–5% yield loss occurred, respectively (Malaker et al. 2016; Callaway 2016; Islam et al. 2016; Chowdhury et al. 2017). Presently the disease is under monitoring and surveillance, and short-, medium-, and long-term research strategies are underway to mitigate the threat of wheat blast (Table 5). *Fusarium* head blight (FHB) is a major concern of many wheat-growing countries wherever it occurred. During the last cropping season (in the year 2018), the disease with high prevalence was observed in a trial of HarvestPlus at WRC-Dinajpur (Reza et al. 2018). Though till now its occurrence in farmer's field in a negligible level. So, if the disease reappeared to the coming year likewise, it might be an issue to pave research priority. Major research thrust was given on screening and evaluation for disease resistance, testing the fungicidal efficacy, and disease monitoring in national and international nurseries and farmers' fields.

Although the invasion of wheat blast is first time reported in Bangladesh in 2016 (Callaway 2016; Islam et al. 2016; Malaker et al. 2016), there is a possibility to spread into South Asia including India, Pakistan, Nepal, and China (Government of India 2016; Press Trust of India 2017). As a result WB incidence in Bangladesh has brought an attention to the governments of different countries in South Asia and the international community of plant pathologists, to expose an urgent need to develop strategies to limit the spread of this destructive pathogen (McDonald and Stukenbrock 2016; Sadat and Choi 2017; Saharan et al. 2016; Sharma 2017; Singh et al. 2016; Ceresini et al. 2018). Mottaleb et al. (2018d) warned that more than 17.1% (nearly 7 million ha) of the total 40.85 million ha of wheat area in Bangladesh, India, and Pakistan is vulnerable to wheat blast, and only a 5% reduction in the wheat production only in the blast vulnerable area can reduce wheat production by 886,000 metric ton worth of US$132 million.

Table 5 Comparative status of blast incidence in 2016, 2017, and 2018

Events	2016	2017	2018
Infection time	Mid-February	Mid-January	Early February
Weather situation	Rain at flowering time (35 mm in Feb) with warm temperature (Min. 18-23 °C, Max. 21-28 °C)	High humidity due to fog at flowering and warm temperature (min. 16–18 °C and max. 24–26 °C)	Fluctuation of day-night temperature (min. 10–12 °C and max. 26–28 °C) with high humidity/fog
Area affected	15,000 ha (DAE)	22 ha (DAE)	–
Yield losses	25–30%	5–10%	1–5%
Districts affected	Meherpur, Jhenaidah, Chuadanga, Jessore, Magura, Kushtia, Barisal, Bhola	Previous districts + some additional districts: Faridpur, Rajshahi, Pabna	Meherpur, Jhenaidah, Chuadanga, Jessore, Kushtia, Bhola, Faridpur, Rajshahi, Rajbari, Natore, Tangail, Jamalpur, Cumilla

Data source: Reza et al. (2018)

Since wheat blast is a threat to wheat production in Bangladesh and South Asia, short-, medium-, and long-term strategies have been formulated to mitigate the threat to sustaining wheat production in this region in collaboration with CIMMYT, ACIAR, and USDA to develop blast-resistant wheat variety.

6.3 Crop Competition in Wheat-Growing Season

One of the major challenges of expanding wheat in Bangladesh is crop competition in the winter. In a study, Mottaleb et al. (2018b) showed that the incidence of wheat cultivation in Bangladesh is mostly limited among the medium and large farm holders in Bangladesh, who have some luxury to allocate land for wheat cultivation after allocating land for *boro* rice. Although Bangladesh achieved self-sufficiency in rice production, excessive extraction of groundwater for rice cultivation especially for irrigating of *boro* rice is a major concern as its cultivation associated with negative impacts on the agroecology and environment (Alauddin and Quiggin 2008). Due to the reliance on groundwater irrigation mainly for *boro* rice, the groundwater levels in Bangladesh have been reportedly declining between 0.01 and 0.05 meter yearly (Shamsudduha et al. 2009; Dey et al. 2013). Other major crops competing with wheat are maize, potato, vegetable crops, etc. The present policy of the government is to promote *aus* rice (upland rice) replacing *boro* rice in high and medium land to save underground water and give more space for winter crops like wheat.

6.3.1 Constraints in Productivity Enhancement and Emerging Challenges

Major production constraints of wheat under Bangladesh context are global warming, short winter, inadequate crop management, less availability of quality seed, slow adoption of new varieties, and the threat of new diseases due to climate change. Depletion of organic matter is another constraint common for all crops that come from high cropping intensity. However, wheat cultivation is less costly, resource-conserving, environmentally friendly, and economically viable. The national average yield during 2001–2008 was around 2.00 t ha^{-1}. However, wheat productivity has started increasing systematically from 2009 and rose to 3.13 t ha^{-1} in 2017 (Index Mundi 2018; Barma 2018). Still, the demonstration average yield of new varieties is about 3.6 t ha^{-1}. At research stations with optimum management, the mean yield of new existing wheat varieties so far recorded is 4.5–6.5 t ha^{-1} (Barma 2018). So, still, there is a yield gap of about 1.4 ton per ha between research station yield and farmers' yield.

6.3.2 High Production Cost and Low Wheat Grain Price

In addition, the per hectare irrigation costs for *boro* rice cultivation are estimated at USD178, whereas it is only USD76 for wheat (Lagos and Hossain 2016). Consequently, the overall production costs of *boro* rice are relatively high compared to wheat. For example, the per hectare production cost of *boro* rice is reported as US$ 913–1319, while for wheat it is US$ 663 (Lagos and Hossain 2016; Sujan et al. 2017; CIMMYT 2015). Consequently, the benefit-cost ratio for *boro* rice in Bangladesh is 0.82, whereas for wheat it is calculated as 1.24 (Lagos and Hossain 2016). It means the return from boro rice after USD100 will be USD 82, but it will be US$ 124 in the case of wheat. As wheat consumption in Bangladesh has been increasing rapidly, and as marginal return from wheat is higher than *boro* rice, there is a large potential for wheat cultivation expansion in Bangladesh.

7 Breeding and Biotechnological Approaches to Improve Stress Tolerance Wheat in Bangladesh

The yield potentiality and disease resistance of the upcoming varieties are to be increased to enhance wheat production in the country, which can be achieved through good agronomic management. Yield potential can be increased through strategic crosses based on pyramiding yield potential traits, disease resistance, physiological traits conferring tolerance to abiotic stresses, etc. in the agronomically superior adapted genotypes. Thus, the main objective of hybridization is to create variability by combining and recombining desirable genes in the background of different adapted genotypes followed by a selection of desirable plants in subsequent generations to develop improved varieties for the target environment. Major focus has been given to developing high-yielding, disease-resistant, and stress-tolerant variety with a wide range of adaptability.

Development of abiotic stresses such as heat drought and salinity tolerant and also wheat blast-resistant variety has been given the highest research priority under the context of global climate change. Marker-assisted selection has been introduced to develop multiple stress-tolerant varieties. Development of varieties with the improved nutritional quality especially Zn content has been addressed in the program. The performance of newly developed wheat lines from national and international sources especially CIMMYT is being evaluated under different growing environments across the country.

7.1 Development of Abiotic Stress Resistance Varieties/Lines Under Changing Climate

7.1.1 Development of Wheat Varieties Tolerant to Early- and Late-Sown Heat Stress

Every crop has an optimal temperature range for growth and development, and temperature below or exceeding the upper limit hampers the life cycle of affected crops that leads to decrease in the final yield. A decrease in the production of *aman* (monsoon rice) rice by 2.94, 53.06, and 17.28 tons, respectively, was due to a 10 °C increase in maximum temperature at vegetative, reproductive, and ripening stage (Islam 2008). An increase in winter temperature by 2–4 °C may exceed the loss by 60% of the achievable yields of wheat and potato (Karim 1993; Islam 2008). Subsequently, the temperature sensitivity also affects the soil respiration and soil organic matter decomposition (Leite and Madari 2011).

In Bangladesh, some areas of lands become vacant in late October to early November due to the expansion of short duration rice varieties which is suitable for growing wheat. But seeding of wheat during this period is not yet recommended. Temperature remains comparatively high during this period which has a detrimental effect during germination and crop establishment stages causing considerable yield loss. Heat stress during early crop growth is called “juvenile heat stress” which causes less biomass, less tillering, i.e., poor crop stand, shortened vegetative period, i.e., early heading with less number of grains per spike, and reduced spike length. Sometimes optimum sown wheat also suffers from early heat stress. Usually, farmers don’t like to hold their land empty for a long time to avoid loss of residual soil moisture. Development of early heat-tolerant wheat line/variety has great potential to increase the area and productivity of wheat. The research program has been initiated to evaluate and select promising wheat genotypes with early heat tolerance and high-yield potential suitable for early seeding.

On the other hand, one of the major constraints for wheat production in Bangladesh is late planting, due to the late harvest of T. *aman* rice. Late-planted wheat is facing high-temperature stress during grain filling which shortens the grain filling period, resulting in shriveled grain that leads to low yields. So, top research priority has been given for the development of heat-tolerant variety suitable for the late-sown environment. Therefore, all the genotypes developed from national and international sources are screened under heat stress condition manipulating sowing dates. Morphophysiological traits related to heat tolerance traits are being incorporated in the adapted genotypes through hybridization to develop high-yielding heat-tolerant wheat varieties. WRC has already released 33 high-yielding, abiotic and biotic stress-tolerant varieties for commercial cultivation (Table 2).

7.1.2 Technologies for Enhancing Wheat Areas in Dry Land

Wheat in Bangladesh is subjected to multiple simultaneous stresses like heat and drought. Bangladesh is at higher risk from moisture stress, 3.5 million ha land is affected by drought, and wheat is one of the major cereal crops under this threat which affected about 47% area of the country and 53% of the population (Alam 2015). However, due to changing climate, the incidence and intensity of drought are increasing. Due to global warming, in the last 25 years, already four major droughts have occurred mostly in northwestern Bangladesh (Selvaraju et al. 2006) during *rabi* (dry/winter) season (Huq 2006). The devastating and regular droughts occurred due to the lack of late rainfall. In the years 1973, 1978–1979, 1981–1982, 1989, 1992, and 1994–1995, Bangladesh already has faced major droughts. In the year 1978–1979, due to drought 50 to 100%, more food grain production was loosed, which the greater than that of the flood in 1974 (Selvaraju et al. 2006). According to IPCC awareness report, rice yield potentiality will be reduced by 8% and wheat yield by 32% within 2050 in Bangladesh (Hossain and Teixeira da Silva 2013).

Drought-tolerant genotypes provide a comprehensive approach for mitigating production-related risk that influences wheat production in Bangladesh. Screening of wheat genotypes under drought stress environment has been initiated at Rajshahi to identify drought-tolerant varieties. Incorporation of drought tolerance characters into adapted varieties is also under progress. Emphasis has also been given to collect and evaluate germplasm from national and international sources to screen against drought stress environment especially in Barind area of Rajshahi. Besides, resource-conserving technologies like a raised bed, strip tillage, etc. along with crop residue incorporation are suggested for drought-prone areas to manage drought stress. Considering the importance of the issue, researchers in WRC of BARI studied 35 genotypes under drought and well-watered condition in 2 consecutive years. Based on the changes in growth phenomena, dry matter production and partitioning, changes in physiological activities, remobilization of pre-anthesis assimilates to the reproductive organ, and grain yield under drought condition, the genotypes “BARI Gom 26” and “BAW 1169” were recommended for drought-prone region of Bangladesh (unpublished data, Table 6).

Table 6 Three wheat genotypes and their pedigree evaluated under water-deficit condition

		Grain yield (t ha^{-1})		
Genotypes	Cross/pedigree	Well-watered	Drought	% Reduction
BARI Gom 26	ICTAL123/3/RAWAL87//VEE/HD2285 BD (JOY) 86-0JO-3JE-010JE-010JE-HRDI-RC5DI	5.59	4.04	27.67
BAW 1169	SHATABDI/BAW 923 BD(DI) 1134S-0DI-4DI-010DI-010DI-1DI-DIRC3	5.41	2.95	45.53
BAW 1167	BL 3877 = KAUZ/STAR/CMH 81.749//BL 2224 NC 02B3616-5B-020 M-020B-3B-0B	5.18	3.44	33.56
LSD (5%)		0.60		
CV (%)		7.04		

7.1.3 Development of Varieties/Lines for Coastal Salt Regions of Bangladesh

Similar to heat stress and drought, salinity is one of the major limitations to wheat production worldwide including the southern part of Bangladesh (Parida and Das 2005; Fahad et al. 2015). Most of the coastal areas are located in the southern part of Bangladesh under the medium high land category (Rahman and Ahsan 2001). Out of 2.85 million hectares of coastal areas of Bangladesh, nearly 0.84 million hectares are affected by varying intensities of salinity (Karim et al. 1990).

Introduction of salinity-tolerant crop varieties for overcoming the salinity problem has been considered the most feasible and economic, and it has recently received much attention (Ashraf and Wu 1994). So far only one saline-tolerant variety “BARI Gom 25” has been developed by WRC. Screening is the most important procedures to find out the salt-tolerant genotypes of crops from available germplasm. Characters such as germination, survival, and seedling growth or biomass accumulation have been the most commonly used criteria for identifying salinity tolerance in plants (Khan et al. 2007; Akram et al. 2010). Salt tolerance, however, is usually assayed in terms of absolute or relative growth or yield (accumulation of biomass or grain yield) (Khan et al. 2007). Because biomass production under saline conditions is one of the important traits for high yield. Therefore, screening a large number of genotypes for seedling growth under high salinity has been initiated saline-tolerant cultivar or introducing the screened material for cultivation on salt-affected soils. Moreover, a collaborative research program in collaboration with CSIRO, Australia, with ACIAR support has been undertaken to incorporate saline tolerance in adapted genotypes.

Nowadays, the scope of expanding wheat in the traditional area is very limited due to completion with other crops in *rabi* season (Rawson et al. 2007; Rawson 2011). So, wheat may be expanded to the southern coastal region of Bangladesh where such huge area remains fallow in *rabi* dry season with varying levels of salinity (Karim et al. 1990). The research program is underway to develop wheat varieties which are suitable to cultivate in coastal saline regions of Bangladesh (Khan et al. 2018; Table 7). During 2017–2018, a total of 24 wheat genotypes were tested in four saline-tolerant locations to select the saline-tolerant wheat genotypes under ACIAR that supported the project. On the basis of field performance and yield data, genotypes “BARI Gom 25,” “BARI Gom 29,” “BARI Gom 30,” “BARI Gom 33,” “BAW 1147,” “BAW 1208,” “BAW 1272,” “BAW 1290,” “BAW 1293,” and “KRL-210” were found salt tolerant in coastal four selected districts of Bangladesh (Table 7).

7.1.4 Accelerating Variety Release Through Doubled Haploid Breeding

The conventional breeding method requires several generations for getting homozygous lines to develop wheat varieties which is a time-consuming process. The

Table 7 Yield performance of 24 wheat genotypes under varying levels of salinity (2.56–4.29 dS m^{-1}) in four coastal districts of southern Bangladesh

	Yield (kg ha^{-1})							
Genotype	Barishal 1	Barishal 2	Patuakhali 1	Patuakhali 2	Khulna 1	Khulna 2	Satkhira 1	Satkhira 2
BARI Gom 21	2650	3670	2040	2460	2940	3420	1520	1380
BARI Gom 23	2200	3270	2100	2780	2900	3060	2760	1590
BARI Gom 24	3070	3840	2090	2860	2910	3400	2300	1460
BARI Gom 25	2590	2780	2060	2640	3450	3790	2580	1530
BARI Gom 26	2690	3500	2030	2720	3480	3210	2320	1300
BARI Gom 27	2260	3540	2160	2830	3510	3530	2750	2050
BARI Gom 28	2920	4250	2050	2560	4180	3810	2400	1660
BARI Gom 29	3600	3310	1990	2590	3480	3840	2250	2120
BARI Gom 30	2310	3160	1960	2390	3910	3850	2380	1800
BARI Gom 31	3350	3670	2220	2830	3790	3770	2720	580
BARI Gom 32	2520	2930	2170	2560	3060	3300	2140	1670
BARI Gom 33	2980	3580	2020	2590	2880	3110	2080	1540
KRL 1–4	1910	2310	2100	2850	2960	3060	2300	750
KRL 19	2820	2720	2030	2720	3090	3180	3070	2140
KRL 210	2650	3570	1910	2220	3290	3450	2480	1370
BAW 1147	3060	3340	2510	2990	2890	3220	2780	1490
BAW 1194	2990	3810	1960	2080	3560	3790	2490	1550
BAW 1208	2720	3020	2280	2900	3360	3350	2570	2380
BAW 1272	2340	3100	2130	2790	3700	3840	2440	1270
BAW 1280	3330	3210	2110	2690	3170	3400	2460	1680
BAW 1286	2710	3620	1880	2490	2870	3100	2470	1180
BAW 1290	2860	4230	2020	2140	3360	3450	2750	1830
BAW 1293	3910	4250	2140	2930	2810	3300	2140	1440
BAW 1295	2420	2640	1810	2200	3140	3430	1010	670
Min.	1910	2310	1810	2080	2810	3060	1010	580
Max.	3910	4250	2510	2990	4180	3850	3070	2380
Mean	2780	3390	2070	2620	3280	3440	2380	1520

Adapted from Khan et al. (2018)

production of doubled haploid (DH) facilitated development of homozygous lines from a crop plant instantly. The selection efficiency depends on uniform homozygous line production which facilitates better discrimination among genotypes within only one generation in breeding nurseries, building it a valuable technique for both wheat breeding and genetic studies.

Within a relatively short time, anther culture is one of the most important plant breeding techniques to produce new homozygous genotypes (Flavell 1981). However, this technique may cause undesirable genetic alterations due to gametoclonal variation (Huang 1996; Raina 1997). The means and genetic variances can be affected by these factors in a breeding population, thus hampering selection of population (Ma et al. 1999). Furthermore, DHs of wheat can be made by interspecific crosses. In DH method, the selective elimination occurs during embryogenesis of alien chromosomes; as a result haploid embryo appears.

Firstly, barley (*Hordeum bulbosum*) was used as the pollen parent for DH (Barclay 1975). Though most of the wheat genotypes show disability of cross with *Hordeum bulbosum* due to the presence of dominant allele *Kr1* on chromosome 5B and/or allele *Kr2* on chromosome 5A (Snape et al. 1979), these two dominant alleles *Kr1* and *Kr2* are responsible for the limited crossability.

In contrast, haploid wheat plants produced through wheat x maize cross and recalcitrant genotypes have not been seen because the chromosomes of maize are eliminated at early embryonic stages (Laurie and Bennett 1988), and *Kr* genes cannot affect the efficiency of haploid production (Laurie and Bennett 1988). Several studies have been proven that different species such as sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) are also possible pollinators for wheat haploid production (Ahmad and Comeau 1990; Inagaki and Mujeeb-Kazi 1995). WRC already adopted the protocol of doubled haploid through wheat x maize cross-pollination. Two young scientists have been trained, and by this time good progress was made in producing doubled haploid plants of targeted crosses.

In addition to this, a project has been undertaken to develop speed breeding facilities to advance the generation quickly and to shorten the variety release time.

7.1.5 Genetic Gain of Wheat Varieties in Bangladesh

Wheat Research Center (Barma 2018) has so far developed 33 wheat varieties until 2017. The rapid adoption of new varieties and other improved production technologies causes a substantial yield increase in recent years and the ever highest national average yield of 3.13 t ha^{-1}. The recognition of increased yield will be realized by significant use of the genetic values of varieties, amended agronomy, irrigation, and proper fertilization. It is necessary to document the genetic gains in grain yield of recently released varieties under fungicide spray and unsprayed with irrigated timely sown (ITS) conditions to support in the future wheat breeding program.

The mean performance of all varieties over both sprayed and unsprayed condition is presented in Table 8. The mean effect for all traits was statistically significant. Among the varieties, "BARI Gom 32" was the earliest maturing and dwarf in stature,

Table 8 Interaction effect of variety and fungicide sprayed condition on grain spike^{-1}, TGW, spikelet spike^{-1}, and yield

Variety	Grain spike^{-1}		TGW (gm)		Spikelet spike^{-1}		Yield (kg ha^{-1})		% Of yield lose for unsprayed wheat
	Sprayed	Unsprayed	Sprayed	Unsprayed	Sprayed	Unsprayed	Sprayed	Unsprayed	
Sonalika	50	49	43.6	43.3	17	16	4923	4200	15
Kanchan	50	44	48.9	41.6	20	18	6160	5436	12
Shatabdi	53	51	47.3	47.7	17	17	6137	4611	25
Prodip	52	47	58.4	57.1	20	18	5733	5690	1
BARI Gom 26	54	54	49.8	49.3	17	17	6460	6308	2
BARI Gom 28	53	43	48.5	50.4	17	15	6314	5910	6
BARI Gom 30	43	44	53.6	48.4	14	15	6023	5619	7
BARI Gom 32	35	37	57.5	54.2	15	15	5450	5589	-3
F-test	ns		**		ns		ns		
LSD (0.05)	–		2.34		–		–		
CV (%)	10.8		2.8		8.9		4.5		

Adapted from Alam et al. (2018

** 5% level of significance; ns non significance) which can escape terminal heat stress and also lodging. “Kanchan” released in 1983 still produced the highest number of spikes m^{-2} (492) followed by “BARI Gom 28” and “Shatabdi.” The highest grain $spike^{-1}$ was found in Shatabdi followed by “BARI Gom 26” and Prodip. The highest TGW was recorded in “Prodip” (57.8 g) followed by “BARI Gom 32” (55.9 g) and “BARI Gom 30” (51 g). The highest number of spikelet $spike^{-1}$ is also recorded in Prodip. Under the sprayed condition, “BARI Gom 26” produced the highest yield (6384 kg ha^{-1}) followed by “BARI Gom 28” (6112 kg ha^{-1}) and “BARI Gom 30” (6023 kg ha^{-1}) (Alam et al. 2018; Table 8).

The highest yield loss (25%) was recorded in Shatabdi released in 2000 in comparison to unsprayed condition (Fig. 6). The yield of “BARI Gom 32” was higher under an unsprayed condition which might be due to better resistance to foliar diseases. However, the wheat varieties of newly released (“Prodip,” “BARI Gom 26,” “BARI Gom 28,” and “BARI Gom 30”) showed very insignificant yield loss in comparison to unsprayed than previously released wheat varieties (“Sonalika,” “Kanchan,” “Shatabdi”). The average yield of sprayed wheat is slightly higher ($y = 0.1838x - 315.16$) than unsprayed wheat ($y = 0.3123x - 576.75$). In this year, the temperature was favorable during the wheat-growing period. Therefore, the BpLB and leaf rust were lower compared with other years. So, the yield loss for unsprayed was low in Dinajpur.

7.2 Development of Biotic Stress-Tolerant Variety/Genotype Under Changing the Climate

7.2.1 Development of Wheat Variety/Genotype Tolerant to *Bipolaris* Leaf Blight

Considering the nature of the damage and wide occurrence throughout the country, *Bipolaris* leaf blight (BpLB) caused by *Bipolaris sorokiniana* (teleomorph, *Cochliobolus sativus*) is the most important disease of wheat in Bangladesh. Not only leaf blight but the pathogen also causes seedling blight, head blight, and black point disease of wheat (Goswami et al. 2004). High degree of resistance to BpLB almost lacks in the cultivated varieties. Seed-borne nature, wide genetic and environmental variability, and wide host range (Duveiller and Gilchrist 1994) of the pathogen are the main problems toward developing resistant varieties. The severity of the disease increases with plant age, and disease development becomes faster during grain filling period when high temperature accompanied by high relative humidity prevails (Alam et al. 1994). Evaluation of varieties or lines against different diseases under the inoculated condition is an essential prerequisite toward the development of resistant varieties. In the context, researchers of WRC are working hard to develop varieties that are resistant against BpLB.

An effort was made by researchers of Reza et al. (2018) to evaluate the reactions of 56 wheat genotypes consisting of advanced lines and check varieties against

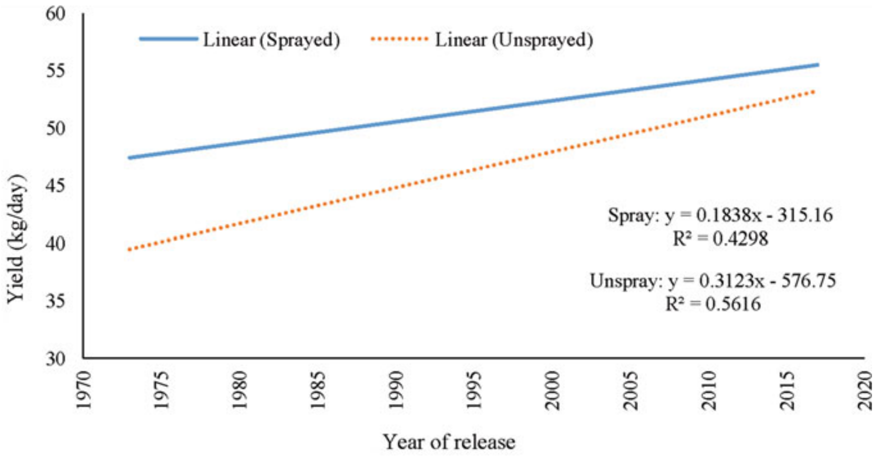

Fig. 6 Comparison of genetic gain in grain yield (kg day^{-1}) of spray and un-spray of eight popular wheat varieties in Bangladesh. (Adapted from Alam et al. 2018)

Bipolaris leaf blight under inoculated condition. The tested varieties and lines showed different levels of resistance and susceptibility against the disease. Among the tested 56 genotypes, 2 were found as resistant, 8 were moderately resistant, 19 were each moderately susceptible, 19 were susceptible, and the rest 8 were as highly susceptible (Table 9).

7.2.2 Development of Wheat Genotypes Tolerant to Leaf and Stem Rust

Among the three wheat rust diseases in Bangladesh, leaf or brown rust caused by *Puccinia triticina* Eriks. is the second most important disease after *BpLB*. Depending on genotypes, sowing times, and locations, the disease occurs all over the country with varying levels of severity. Yield losses due to leaf rust are usually less than 10% but can be increased 30% or more depending on the level of susceptibility, environmental conditions, and the stage of the crop (Singh et al. 2002). In Bangladesh, the disease generally appears in mid-February, and severity is increasing between mid and late March. However, severity is high in late-planted wheat than those planted in optimum times. But losses would be significantly higher if a susceptible variety is grown under late-sown condition.

Use of resistant variety is the most dependable and economic approach for the control of the rust diseases. Therefore, major emphasis has been given to screen breeding lines against leaf rust under field and inoculated condition toward the development of resistant varieties. A group of leaf rust-resistant varieties/lines with the existence of different *Lr* genes is being maintained in a crossing block. Hybridization program has been going on to incorporate different *Lr* genes to the adapted genotypes for developing varieties with durable resistance. Based on

Table 9 Grading of wheat genotypes against BpLB under inoculated condition

Variety/line	% DLA on F leaf	Reaction
Chirya 7 and Milan/Sha 7 = 2	≤ 10	Resistant
BAW1254, BAW1295, BAW1316, BAW1317, Shatabdi, BARI Gom 29, BARI Gom 30, and BAW1300 = 8	11–30	Moderately Resistant
BAW1203, BAW1208, BAW1243, BAW1272, BAW1280, BAW1303, BAW1318, BAW1322, BAW1325, BAW1326, BAW1328, BAW1331, BAW1334, BAW1337, WBSN75, WBSN92, BARI Gom 31, BARI Gom 32, BARI Gom 33 = 19	31–50	Moderately Susceptible
BAW1194, BAW1286, BAW1293, BAW1296, BAW1297, BAW1299, BAW1304, BAW1324, BAW1327, BAW1329, BAW1332, BAW1333, BAW1335, BAW1338, WBSN81, Prodip, BARI Gom 25, BARI Gom 26, and BARI Gom 28 = 19	51–70	Susceptible
BAW1290, BAW1321, BAW1323, BAW1330, BAW1336, Sonalika, Kanchan, and CIANO 79 = 8	>70	Highly Susceptible

Adapted from Reza et al. (2018)
Scale used for grading lines into resistance category: % disease severity, resistant (0–10), moderately resistant (20–30), moderately susceptible (40–50), susceptible (60–10)

Table 10 Grading wheat genotypes into resistance category

Variety/line	Leaf rust score	Resistance category
BAW1203, BAW1286, BAW1338, BARI Gom 27, BARI Gom 28, BARI Gom 29, BARI Gom 30, BARI Gom 31, BARI Gom 32, BARI Gom 33, Shatabdi, Sourav, Bijoy, CIANO 79, BAW1194, BAW1208, BAW1243, BAW1254, BAW1272, BAW1280, BAW1290, BAW1293, BAW1295, BAW1296, BAW1297, BAW1299, BAW1304, BAW1316, BAW1317, BAW1321, BAW1322, BAW1323, BAW1324, BAW1325, BAW1326, BAW1327, BAW1329, BAW1330, BAW1331, BAW1334, BAW1335, BAW1336, BAW1337, BAW1300 = 44	0-10MSS	Resistant
Sonora 64, Kalyansona, Sonalika, Prodip, BARI Gom 25, BARI Gom 26, BAW1303, BAW1318, BAW1328, BAW1332, and BAW 1333 = 11	20–30S	Moderately resistant
Dirk	40–50S	Moderately susceptible
Morocco	60–100S	Susceptible

Adapted from Alam et al. (2018)
Resistance category: resistant (R) = 0–10%, moderately resistant (MR) = 20–30%, moderately susceptible (MS) = 40–50%, susceptible (S) = 60–100% severity

disease severity, most of the newly released varieties are resistant/moderately resistant to leaf rust, and among those "BARI Gom 27" and "BARI Gom 30" were found completely free from leaf rust. Based on disease severity, most numbers of advanced lines have been identified as resistant to leaf rust (Alam et al. 2018; Table 10).

7.2.3 Development of Wheat Genotypes Resistant to Stem Rust

Stem rust caused by *Puccinia graminis* f. sp. *tritici* is an important disease of wheat, particularly in Africa. In Bangladesh, the disease was not observed in the last three decades, but recently in 2014, it was detected in some entries of the rust trap nurseries. So, this is not unlikely that the disease will appear on a large scale in the future and cause damage to wheat. A virulent race of stem rust called *Ug99* was identified in Uganda in 1999 (Pretorius et al. 2000) and subsequently found in epidemic proportions in Kenya and Ethiopia. Sudan, Yemen, Iran, and Tanzania are also affected, and some variants of the race have been confirmed in those countries including South Africa, Mozambique, and Zimbabwe (Singh et al. 2011). The experts of Borlaug Global Rust Initiative (BGRI) have predicted the further movement of *Ug99* and other virulent strains to the important wheat production areas of the Indian subcontinent and beyond (Singh et al. 2008). CIMMYT has developed some wheat germplasms with a good level of stem rust resistance and high-yield potential. The materials were distributed worldwide through Stem Rust Resistance Screening Nursery (SRRSN) for direct release or use in breeding programmers to mitigate the threat of stem rust. Scientists in WRC of BARI are trying to develop wheat genotypes which are resistant against stem rust of wheat. Every year advances lines, and selected segregating generations are sent to KALRO, Kenya, to screen the germplasm against *Ug99* in collaboration with CIMMYT. Among the recent commercial varieties, “BARI Gom 26,” “BARI Gom 27,” and “BARI Gom 29” were found resistant to stem rust (*Ug99* race) (Table 4).

7.2.4 Development of Wheat Genotypes Resistant to Wheat Blast

Wheat blast is a devastating disease and appeared as a new threat to wheat production in Bangladesh and South Asia. As a short-term solution, appropriate fungicides at an affordable price have been suggested to the farmers to control the disease, especially in the blast-conducive environments. However, a long-term and sustainable solution development of blast-resistant wheat varieties is the most important. Therefore, there is a critical need for identification of new sources of resistance to WB and development of blast-resistant wheat variety. A comprehensive breeding program has been undertaken to identify sources of resistance to WB, and their deployment adapted wheat genotypes in collaboration with CIMMYT/ACIAR. A precision phenotyping platform (PPP) has been established at Jessore for large-scale screening against WB with the support from CIMMYT and ACIAR (Fig. 7). During the 2017–2018 wheat season, about 5000 germplasms were received from CIMMYT and have been screened against WB, and some resistant genotypes have been identified.

In the meantime one blast-resistant variety “BARI Gom 33” has been released in the year 2017, which possesses 2NS translocation and is enriched with zinc (50–55 ppm). Three other varieties such as “BARI Gom 21” (Shatabdi), “BARI Gom 30,” and

Fig. 7 Precision phenotyping platform (PPP) at RARS, Jessore for wheat blast (WB). In 2017–2018 about 5000 germplasm including elite and advance lines have been screened against WB through the help of CIMMYT-ACIAR. (Adapted from Reza et al. 2018)

“BARI Gom 32” showed a moderate level of tolerance to WB, where most popular variety “BARI Gom 26” was found the most susceptible to WB (Table 4).

7.2.4.1 Genomic DNA Extraction

For each wheat genotype, to amplify 2NS translocation, genomic DNA was extracted from wheat seedlings of 10-day-old using CTAB (cetyl trimethylammonium bromide) method discovered by Stein et al. (2001).

It is well known that 2NS translocation-based blast resistance is working well in many backgrounds and is being utilized for developing blast-resistant varieties. This translocation occurred from *Aegilops ventricosa* of 2NS chromosome arm, a segment of 25–38 cM to the 2AS distal region in the wheat chromosome. Kohli et al. (2011) reported that wheat genotype Milan derived from the CIMMYT line showed high levels of resistance against wheat blast under field conditions, though the genetic basis of resistance has not yet been discovered in Milan (Kohli et al. 2011). Now, the blast resistance source of other genotypes is widely deployed, but it should be effective for long duration (Kohli et al. 2011). Scientists of the Bangladesh Wheat and Maize Research Institute have initiated screening of blast-resistant wheat genotypes using 2NS markers. Moreover, a number of crosses have been made between genotypes having 2NS translocation and non-2NS translocation to develop 2NS-based blast-resistant varieties.

In the year 2017–2018, 80 wheat genotypes (58 advance lines from different nurseries/trials and 22 wheat varieties) were evaluated for blast resistance using a 2NS marker (adapted from Alam et al. 2018; Table 11). The genomic DNA extraction and PCR amplification and gel electrophoresis methods were followed to run the marker. Details describing these screening methods are as follows:

7.2.4.2 PCR Amplification and Gel Electrophoresis

The specific primer of 2NS VENTRIUP (5′-AGG GGC TAC TGA CCA AGG CT-3′), LN2 (5′-TGC AGC TAC AGC AGT ATG TAC ACA AAA-3′) (Cruz et al. 2016) was used for screening wheat blast-resistant genes in a 2NS segment of wheat germplasms. The reaction volume of PCR was 10 μL and performed using a Veriti Thermal Cycler (Applied Biosystems, USA). The reaction product contained 40–100 ng of genomic DNA, 2× PCR master mix, and 10 μM each primer and ddH$_2$O. The amplification program of VENTRUIP-F/LN2-R was as follows: 94 °C for 3 min (enzyme activation); 30 cycles of 94 °C for 45 s (melting), 65 °C for 30 s (annealing), and 72 °C for 60 s (extension); and 7 min for final extension at 72 °C. After PCR, the products (10 μl each) were stained with ethidium bromide (EtBr) and run on 1.5% agarose gel.

After observation primer (VENTRUIP-F/LN2-R) was confirmed that one commercial variety ("BARI Gom 33"), two advanced lines ("BAW 1300" and "BAW

Table 11 Pedigree of wheat genotypes having 2NS translocation

SL. no.	Nursery	Variety/ BAW	Pedigree/selection history
1	Variety	BARI Gom 33	KACHU/SOLALA
			CMSS09Y00580S-099Y-38 M-0WGY-4B-0Y
2	CVD	BAW 1280	BAJ #1*2/TECUE #1
			CMSS07Y01100T-099TOPM-099Y-099 M-099Y-1 M-0WGY
3	CVD	BAW 1300	ROELFS-F-007/4/BOBWHITE/NEELKANT//CATBIRD/3/CATBIRD/5/FRET-2/TUKURU//FRET-2
			CMSS-06-Y00605T-099TOPM-099Y-099ZTM-099Y-099 M-11WGY-0B
4	BWSN-2	E-21	PRODIP/BAW 1075
			BD11JA1823S-099JA-50JA-50JA-30JA-5JA
5	BWSN-2	E-46	T.DICOCCONCI9309/AE.SQUARROSA(409)//MUTUS/3/2*MUTUS
			CMSS12B01381T-099TOPY-099 M-099Y-39 M-0WGY
6	BWSN-2	E-73	KVZ/PPR47.89C//FRANCOLIN#1/3/2*PAURAQ/4/UP2338*2/KKTS*2//YANACMSS11Y00500S-099Y-099 M-3WGY-0B
7	BWSN-2	E-74	MELON//FILIN/MILAN/3/FILIN/5/CROC_1/AE.SQUARROSA 4)/3/T.DICOCCONPI94625/AE.SQUARROSA (CMSS10B00690T-099TOPY-099 M-099Y-20 M-0WGY

Adapted from Alam et al. (2018)

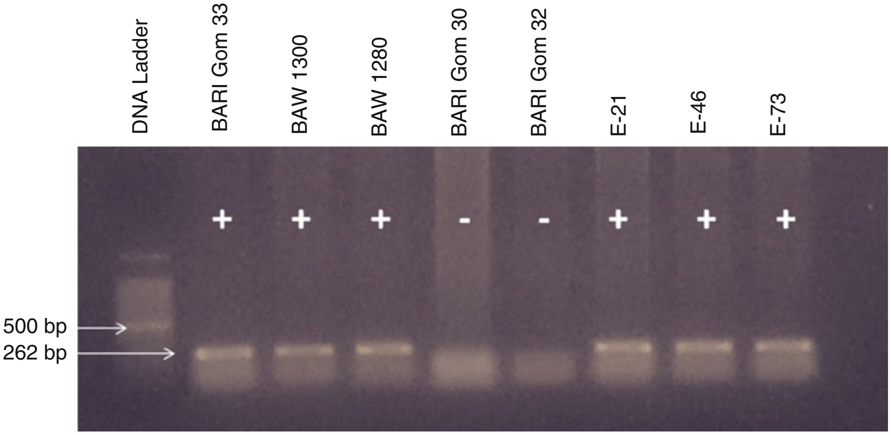

Fig. 8 PCR amplification with 2NS specific primers VENTRUIP-F/LN2-R. (Adapted from Alam et al. 2018)

1280"), and four genotypes from BWSN-II (Bangladesh Wheat Screening Nursery-II) ("E-21," "E-46," "E-73," and "E-74") contain blast resistance genes in 2NS segment (Alam et al. 2018; Fig. 8). The pedigree and blast reaction under field condition in irrigated late sown (ILS) at Jessore location of 2NS translocated genotypes are presented in Table 11. All of 2NS translocated wheat genotypes showed "0" reaction where susceptible check showed 75% wheat blast severity. Research findings of this experiment will be helpful for detecting 2NS translocated wheat genotypes for developing high-yielding blast-resistant wheat varieties through marker-assisted selection.

Therefore it is concluded that this used primer was found to be very useful. For detecting blast-resistant genes in 2NS translocation in wheat and can be used for screening blast-resistant wheat genotypes. This diagnostic marker can also be used in a different filial generation (F_1 to F_6) through MAS method in the national wheat breeding program.

Screening by applying high disease pressure would be helpful in selecting the best varieties among a lot which have the potential to be served as genetic stock for the subsequent use of breeders. In the context, a total of 25 elite wheat genotypes were evaluated against wheat blast and collected from different sources including check varieties under an artificially inoculated condition at RARS Jessore during 2017–2018 (Reza et al. 2018).

As the location was found favorable for wheat blast according to previous 2-year disease data, the tested varieties/lines showed varying levels of resistance and susceptible reaction against the disease. Seven genotypes were scored as resistant, six moderately resistant, seven moderately susceptible, and the rest five as highly susceptible. Disease scoring was done based on the standard scale of 0–100. Among the genotypes, seven genotypes were found resistant based on % disease severity (blast). Percentage of disease severity of those resistant lines ranged from 0% to 10%. The

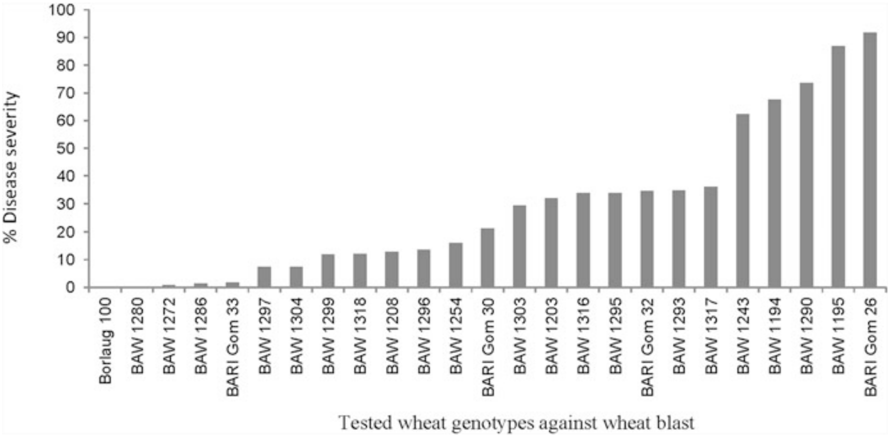

Fig. 9 Elite germplasm screening against WB under artificially inoculated condition. (Adapted from Reza et al. 2018)

resistant variety "BARI Gom 33" was found with 1.8% disease severity, while the most susceptible variety "BARI Gom 26" observed about 91.7%. Genotypes "BAW 1300," "BAW 1272," "BAW 1280," and "BAW 1286" were found as most promising for further evaluation in the next season to release as varieties (Fig. 9).

7.2.5 Technologies for Enhancing Wheat Blast Management

7.2.5.1 Integrated Approaches to Mitigate the Threat of Wheat Blast at a Glance

WB is a devastating disease and established in the southwestern region of Bangladesh, and complete eradication is not possible. Moreover, any single approach will not be worthwhile to control the disease. Therefore, the adoption of integrated approaches is very important to manage the disease at a lower level. Few of the integrated approaches adopted in Bangladesh are shown below:

- Awareness creation among wheat growers and all stakeholders is highly important in the short term.
- Collection of seed from the disease-free area.
- Seed treatment with proper fungicide to reduce the initial load of inoculum.
- Optimum sowing of the crop to avoid disease infection.
- Use of resistant ("BARI Gom 33") and tolerant varieties ("BARI Gom 30," "BARI Gom 32").
- Development and deployment of appropriate fungicides as a preventive spray.
- Collaborative breeding approach to developing blast-resistant variety through national and international support.

- Disease surveillance and monitoring.
- Disease forecasting.
- Quick dissemination of the seed of resistant varieties.
- Human resource and capacity development for wheat blast management.

7.2.5.2 Efficacy of Seed Treating Fungicides in Reducing the Prevalence of Seed-Borne *P. oryzae* and Their Subsequent Effect on Wheat

The WB disease usually occurs on all aerial plant parts, but the most conspicuous symptom is observed on a spike. Severe WB epidemics have coincided with the wet season, warm temperatures, and high humidity. Breakdown of resistance due to the evolution of new pathotype/race may develop epidemic of WB under favorable environmental conditions. In the absence of resistance, seed treatment with fungicides has been considered as an alternative option to reduce the inoculum density at a minimum level (Reis 1991). The use of healthy seeds provides a means of reducing primary inoculum and, in turn, reduces foliage infection and seedling blight. Seed-borne infection can be reduced by treating seeds with different chemicals/fungicides. Management of seed-borne diseases through seed treatment is most economical, durable, and an effective control measure. Nghiep and Gaur (2005) reported that results of vitavax, thiram, and mancozeb were the best to reduce the seed-borne infection as compared to the other chemicals. Several fungicides have been employed in the control of fungal diseases of rice. Among them, carboxin, thiram, mancozeb, and iprodione were reported to be very effective against the disease.

Scientists in WRC of BARI are trying to find out fungicides which are suitable for sustainable wheat production in Bangladesh. In the context, an experiment was conducted in two environmental conditions of Bangladesh: at WRC, Dinajpur (Lab.), and RARS, Jessore (Field), during 2017–2018 crop growing season. Four fungicides of different groups were tested for their efficacy against WB disease and its causal organism. The fungicides, namely, Provax-200 WP (carboxin 37.5% + thiram 37.5%), Vita Flo 200 FF (carboxin 17.5% + thiram 17.5%), Rovral 50 WP (iprodione 50%), and Goldman 80 WP (mancozeb 80%) were tested. An untreated control was also maintained for comparison. The seeds of susceptible variety “BARI Gom 26” were examined with an initial 72% inoculum prevalence on seeds. In the blotter method, 400 seeds were treated separately for each fungicide. All the fungicides were found very effective against *P. oryzae* control (100% control) in laboratory condition in blotter method. Seed treatment with these fungicides also significantly increased plant population over control treatment in field condition, but none of them was found effective in reducing disease incidence. Seeds treated with fungicides not only reduce/control initial inoculums of *P. oryzae* but also control other seed-borne fungi (*B. sorokiniana*, *Alternaria*, *Curvularia*, *Fusarium* sp. etc.) (Reza et al. 2018; Table 12). Seeds treated with these fungicides were found very effective in reducing *P. oryzae* incidence from seeds. Although there was no significant effect on disease control, it keeps initial inoculums to a minimal level.

Table 12 Efficacy of seed treating fungicides in controlling wheat blast/*P. oryzae* at RARS, Jessore 2017–2018

Fungicide	Dose	% disease severity	TGW (g)	Yieldplot^{-1} (g)	Yield increased (%)	Disease/*P. oryzae* controlled (%)	
						Field	Laboratory
Provax 200 WP	3 g kg-^{1} seed	12.3	29.50	548	15	15	100
Vita Flo 200 FF	3 ml kg^{-1} seed	12.6	29.75	533	12	13	100
Rovral 50 WP	3 ml kg^{-1} seed	13.1	32.75	589	24	10	100
Goldman 80 WP	3 ml kg^{-1} seed	11.9	30.50	540	14	18	100
Control (unsprayed)		14.5	29.75	476	0	–	–
LSD $_{(0.05)}$		8.69	3.80	54.57	–	–	–
Level of significance		NS	NS	*	–	–	–

Source: Reza et al. (2018)
* 1% level of significance

Seed treated with fungicides not only reduce/control P. oryzae but also controls other seedborne fungi (*B. sorokinia, Alternaria, Curvularia, Fusarium* sp. etc).

7.2.5.3 Efficacy of Foliar Fungicides in Controlling Wheat Blast

In the absence of resistance, foliar sprays with fungicides have been considered as an interim measure to reduce the disease to a certain level. Among many fungicides, tebuconazole, trifloxystrobin, and tricyclazole were reported to be very effective against the disease.

A study was undertaken to evaluate the efficacy of foliar fungicides in controlling WB under field condition. Six fungicides of different groups were tested for their efficacy against WB. The fungicides, namely, Nativo 75 WG (tebunaconazole 50% + trifloxystrobin 25%), Amistar Top 325 SC (azoxystrobin 20% + difenoconazole 12.5%), Folicur 250 EW (tebuconazole 25%), Opponent 75 WG (tebuconazole 50% + trifloxystrobin 25%), Filia 525 SE (propiconazole 12.5% + tricyclazole 40%), and Trooper 75 WP (tricyclazole 75%) were tested. The fungicides were sprayed twice, once at the heading stage and another at 12–15 days after the first spray. An unsprayed control was maintained for comparison. The susceptible variety "BARI Gom 26" was tested for this study. All of these fungicides were found effective in controlling the disease as compared to control plots. Among them, Opponent 75 WG was found very effective in controlling wheat blast with least disease severity (2%) followed by Filia 525 SE and Trooper 75 WP. The highest yield increase of 38% was obtained from spraying with Nativo 75 WG, which was followed by Amistar Top 325 SC and Folicur 250 EW. The highest net profit was also obtained from spraying with Nativo 75 WG, while the lowest with treatment Folicur 250 EW (Reza et al. 2018; Table 13). The unsprayed plots showed

Table 13 Efficacy of foliar fungicides in controlling wheat blast

Fungicides	Dose	% disease controlled	Yield (kg ha^{-1})	% yield increased	Yield increased (kg ha^{-1})	Fungicide + spraying cost (Tk ha^{-1})	Profit (Tk ha^{-1})
Nativo 75 WG	0.6 g L^{-1}	94	3230	38	897	6575	18,532
Folicur 250 EW	1 ml L^{-1}	93	3063	31	730	4250	12,440
Amistar Top 325 SC	1 ml L^{-1}	94	3060	31	727	5400	14,539
Trooper 75 WP	0.8 g L^{-1}	97	3000	29	667	5808	14,417
Opponent 75 WG	0.6 g L^{-1}	98	3039	30	706	8000	12,956
Filia 525 SE	2 ml L^{-1}	97	2973	27	640	6800	12,520
Unsprayed		–	2333	0	0	–	–
LSD (0.05)		–	95.80	–	–	–	–
Level of significance		–	***	–	–	–	–

Reza et al. (2018)

***means 1% level of significance

with the least disease control. The highest grain yield and net profit were found higher with fungicide Nativo 75 WG sprayed plot, followed by Amistar Top 325 SC and Folicur 250 EW, and the lowest profit and yield were recorded with fungicide Filia 525 SE applied plot (Reza et al. 2018; Table 13).

7.2.5.4 Efficacy of Fungicides in Controlling *Bipolaris* Leaf Blight and Leaf Rust of Wheat

Expression of resistance to *Bipolaris* leaf blight is less sustained under favorable conditions of disease development in the rice-wheat cropping systems of South Asia. In the absence of the good level of resistance, foliar sprays with fungicides have been considered as an alternative option to reduce the disease under field condition (Duveiller et al. 2005). Leaf rust of wheat caused by *Puccinia triticina* Eriks. can also be controlled with the foliar application of fungicides. Among many fungicides, propiconazole and tebuconazole were reported to be effective against both the diseases.

Scientists of WRC are trying to find out suitable fungicides as an alternative of resistant wheat for controlling BpLB and leaf rust under field condition. Seven fungicides were evaluated under field condition for controlling BpLB and leaf rust of wheat. Among the fungicides, four fungicides such as Tilt 250 EC (propiconazole), Folicur 250 EC (tebuconazole), Awal 72 WP (zineb + hexaconazole), and Master Zeb 80 WP (mancozeb) were used as standard check, while the other three, i.e., Amistar Top 325 SC (azoxystrobin 20% + difenoconazole 12.5%), Score 250 EC (difenoconazole 25%), and Nativo 75 WG (tebuconazole 50% + trifloxystrobin 25%), were tested as new fungicides. The fungicides were sprayed twice, once at heading stage and another at 15 days after first spraying. An unsprayed control was maintained for comparison. The susceptible variety Kanchan was used for BpLB and Morocco for leaf rust. All the seven selected fungicides, viz., Nativo 75 WG, Tilt 250 EC, Folicur 250 EC, Master Zeb 80 WP, Awal 72 WP, Amistar Top 325 SC, and Score 250 EC, were found very effective in controlling *Bipolaris* leaf blight and also leaf rust of wheat. These fungicides reduced *Bipolaris* leaf blight by 93–97% with 20–31% increase in grain yield and leaf rust by 98–100% with 151–179% yield increase (Reza et al. 2018; Tables 14 and 15).

8 Improved Agronomic Practices for Enhancing Sustainable Wheat Production Under Changing Climate

8.1 Adjustment of Seeding Time

The optimum time for sowing of wheat is measured to be an important management strategy, because it is under the control of farmers (Laghari et al. 2010).

Table 14 Effect of fungicides on *Bipolaris* leaf blight and yield of wheat cv. Kanchan

Fungicides	Dose	% DLA (F leaf)	TGW (g)	Yield Plot^{-1} (g)	Yield increase (%)	Disease control (%)
Tilt 250 EC	0.5 ml L^{-1}	5.9	41.22	1075	23	94
Folicur 250 EW	0.5 ml L^{-1}	2.6	41.25	1093	25	97
Score 325 EC	0.5 ml L^{-1}	3.4	41.22	1073	22	96
Amistar Top 325 SC	1 ml L^{-1}	5.8	42.03	1102	26	94
Master Zeb 80 WP	2 g L^{-1}	6.9	40.48	1053	20	93
Awal 72 WP	2 g L^{-1}	3.5	41.10	1131	29	96
Nativo 75 WG	0.6 g L^{-1}	2.5	42.65	1151	31	97
Control (unsprayed)		96.0	37.30	876	0	0
LSD (0.05)		4.35	1.52	102.66	–	–
Level of significance		***	***	**	–	–

Data source: Reza et al. (2018)
DLA diseased leaf area, *** = significant at 0.1%
** 5% level of significance

Table 15 Effect of fungicides on leaf rust and grain yield of wheat cv. Morocco

Fungicides	Dose	% DLA (F leaf)	TGW (g)	Yield Plot^{-1} (g)	Yield increase (%)	Disease control (%)
Tilt 250 EC	0.5 ml L^{-1}	0.0	31.27	784	170	100
Folicur 250 EC	0.5 ml L^{-1}	0.0	30.12	783	170	100
Score 325 EC	0.5 ml L^{-1}	0.0	31.77	760	162	100
Amistar Top 325 SC	1 ml L^{-1}	0.0	31.87	773	166	100
Master Zeb 80 WP	2 g L^{-1}	1.5	25.37	730	151	98
Awal 72 WP	2 g L^{-1}	1.3	29.30	752	159	98
Nativo 75 WG	0.6 g L^{-1}	0.0	31.67	809	179	100
Control (unsprayed)		87.0	22.87	290	0	0
LSD (0.05)		2.42	2.88	125.67	–	–
Level of significance		***	***	***	–	–

Data source: Reza et al. (2018)
DLA diseased leaf area, *** 1% level of significance

Mid-November to first week of December is considered as an optimum sowing time of wheat in Bangladesh (Hossain and Teixeira da Silva 2012; Hossain et al. 2013). Temperature above or below optimum limits the growth and development of plant through altering the physiological process of plant (Hakim et al. 2012; Hossain et al. 2012; Hossain et al. 2013). A delay in sowing suppressed yield, caused by a reduction in the yield contributing characters such as tillers, grains spike^{-1}, and grain yield (Ahmed 1986; Tahir et al. 2009; Jahan et al. 2018a, b).

To find out optimum sowing time for specific varieties/genotypes and to identify the heat-tolerant wheat lines for future breeding program to develop heat-tolerant wheat varieties, 50 wheat genotypes were evaluated in the year 2016–2017 under irrigated timely sown (ITS) and irrigated late-sown heat stress conditions of Dinajpur, Joydebpur, and Jessore locations through semiarid wheat yield trial nursery. Among the genotypes, 16 genotypes (i.e., "Gen.-7," "Gen.-9," "Gen.-11," "Gen.-13," "Gen.-14," "Gen.-16," "Gen.-19," "Gen.-22," "Gen.-30," "Gen.-31," "Gen.-33," "Gen.-36," "Gen.-38," "Gen.-40," "Gen.-42," and "Gen.-48") performed better under ILS condition and selected for future breeding program to develop heat-tolerant varieties (Hossain et al. 2018a; Table 16).

Similarly, Jahan et al. (2018a; Fig. 10) conducted a field experiment in 2 consecutive years with three existing wheat varieties ("BARI Gom 26," "BARI Gom 27," "BARI Gom 28") and three advance lines ("BAW 1130," "BAW 1138," "BAW 1140"). These genotypes were evaluated under six sowing conditions of four agroecological zones (AEZs) of Bangladesh to identify wheat genotypes suitable for a heat stress environment by using stress susceptibility index (SSI). Among the genotypes, two existing varieties (i.e., "BARI Gom 28" and "BARI Gom 26") were recorded tolerant against early sowing heat stress, late sowing heat stress, slightly late sowing heat stress, very late sowing heat stress, and extremely late heat stress conditions in four AEZs of Bangladesh, whereas variety "BARI Gom 27" was susceptible to all levels of heat stress conditions. Correlation analysis between GY and SSI also confirmed that two exiting varieties "BARI Gom 28" and "BARI Gom 26" and advance line "BAW 1140" were tolerant against all levels of heat stress conditions; variety "BARI Gom 27" and advance line "BAW 1130" were susceptible against all levels of heat stress conditions.

To confirm the previous recommended sowing times, recently six elite wheat varieties were evaluated under different sowing conditions of Dinajpur, Rajshahi, and Jessore to assess the yield potentiality of recently developed elite wheat varieties in diverse sowing condition, to identify the best seeding condition for a variety, and to find out the heat-tolerant and heat-susceptible variety. After observation, it was noted that under the environmental condition of Dinajpur, it was observed that all of the wheat varieties sown at optimum sowing condition (25 Nov.) produced the maximum yield, while the yield of all varieties was decreased significantly ($P \leq 0.05$) when sown at late, while in the environmental condition of Rajshahi and Jessore, wheat sown on the first week of December (05 Dec.) to mid-December (15 Dec.) performed the best than sown on 25 Nov. Considering the varieties, "BARI Gom 30" (4091.80 kg ha^{-1}) performed the best in all sowing conditions as well as late-sown heat stress condition of Dinajpur, which was significantly alike to "BARI Gom 32" (4021.86) and "BARI Gom 33" (4060.53 kg ha^{-1}), whereas in the environmental condition of Rajshahi, the variety "BARI Gom 33" was recorded with the maximum grain yield (3538.00 kg ha^{-1}) under the sowing condition of Dec. 15 sowing, followed by "BARI Gom 31" (3354.67 kg ha^{-1}) and "BARI Gom 28" at same sowing condition. If we consider the yield performance of all varieties under all

Table 16 Interaction effect of genotype, location and seeding time on TGW, and yield (kg ha^{-1}) of selected wheat genotypes

	TGW (g)						Yield (kg ha^{-1})					
	Dinajpur		Joydebpur		Jessore		Dinajpur		Joydebpur		Jessore	
	(AEZ-1)		(AEZ-28)		(AEZ-11)		(AEZ-1)		(AEZ-28)		(AEZ-11)	
Genotypes	ITS	ILS	ITS	ILS	ITS	ILS	ITS	ILS	ITS	ILS	ITS	ILS
BARI Gom 21	47.3	36.8	51.0	37.4	46.5	34.5	5919	3218	3610	2442	5488	2223
BARI Gom 26	47.1	36.4	50.3	41.8	44.0	32.5	6336	3915	3179	2417	4508	2655
Gen.-7	52.1	39.8	57.9	43.0	52.5	33.0	5719	4610	3570	2020	4313	2403
Gen.-9	52.4	44.3	47.2	40.3	51.0	36.5	5525	5229	3367	2147	4965	3533
Gen.-11	52.8	44.4	46.0	45.0	50.0	35.5	5169	3624	2450	2588	4635	3403
Gen.-13	55.6	45.0	54.2	47.4	50.0	30.5	6280	5491	3640	2355	4555	2630
Gen.-14	52.1	47.4	54.9	47.7	49.5	34.5	5770	5018	3428	2097	4748	2563
Gen.-16	60.0	47.2	56.4	45.3	53.0	38.5	6408	4100	3220	1600	5235	2608
Gen.-19	47.4	39.9	40.9	43.4	45.5	33.0	4408	4398	2377	1789	4283	2845
Gen.-22	56.1	44.3	44.5	41.5	50.5	40.0	6011	5369	2795	2279	4998	2365
Gen.-30	48.6	38.4	46.7	42.0	48.5	31.5	6542	4790	4610	3043	4635	2998
Gen.-31	49.3	39.9	52.3	42.7	46.5	29.0	5240	4095	4610	2770	3940	2270
Gen.-33	56.6	47.3	56.0	48.3	56.5	37.5	4640	4507	3618	2192	4468	2715
Gen.-36	51.0	45.1	51.0	45.1	47.5	39.5	5085	4274	3575	1873	4738	3385
Gen.-38	55.9	47.2	53.4	45.3	51.0	36.5	5721	4447	3842	2340	5050	2510
Gen.-40	59.6	49.3	57.0	48.8	55.0	36.0	6061	4709	3279	2337	4905	3220
Gen.-42	56.4	45.2	54.9	43.9	50.0	32.5	5909	4232	3835	1995	5013	2490
Gen.-48	57.1	47.4	59.9	51.6	57.5	34.0	5100	4506	4432	1875	4150	2188
F-test	**						**					
LSD (0.05)	4.22						827.04					
CV (%)	4.8						11					

Adapted from Hossain et al. (2018a)

ITS irrigated time sowing, *ILS* irrigated late sowing

** 1% level of significance

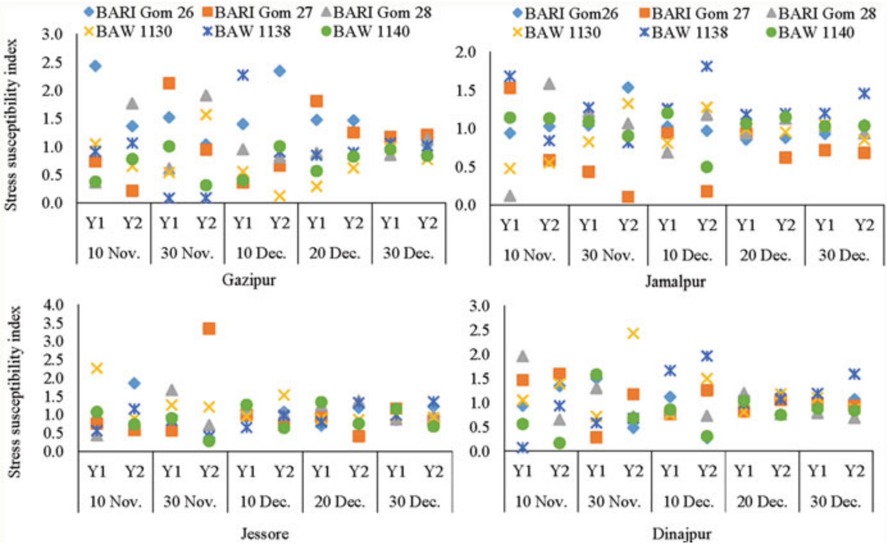

Fig. 10 Stress susceptibility index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012–2013 (Y1) and 2013–2014 (Y2) in four locations of Bangladesh. (Adapted from Jahan et al. 2018a)

sowing conditions of Jessore, “BARI Gom 32” and “BARI Gom 30” produced the statistically similar and the maximum grain yield in all sowing conditions, followed by “BARI Gom 31.” While in Dec. 05, “BARI Gom 32” also produced the maximum yield, this variety also produced the second highest and third highest yield under the sowing condition of Dec. 15 and Dec. 25 in the environmental condition of Jessore. After observation, it was also noticed that location-specific environmental/sowing condition is very important to explore the potentiality of a specific variety (Hossain et al. 2018b; Fig. 11).

8.2 *Optimizing Seeding Rate*

The optimal seeding rate is measured as the best management approach for enhancing the grain yield (GY) of wheat (Sarker et al. 2007; Sarker et al. 2009; Laghari et al. 2010). This is particularly important because it is controlled by farmers (Laghari et al. 2010). However, seeds are a costly input for farmers (Sarker et al. 2009; Farooq et al. 2016). Optimum plant density, which can be achieved by maintaining optimum seeding rate, may vary greatly with the area, climatic conditions, soils, sowing time, variety, and management (Li et al. 2016). Iqbal et al. (2010) and Chauhdary et al. (2016) noticed that if optimum seeding rate is exceeded, GY of wheat may be reduced by stunting the development of tillers and effective tillers; but this can be favored for genotypes which have less tillering habits (Chauhdary et al.

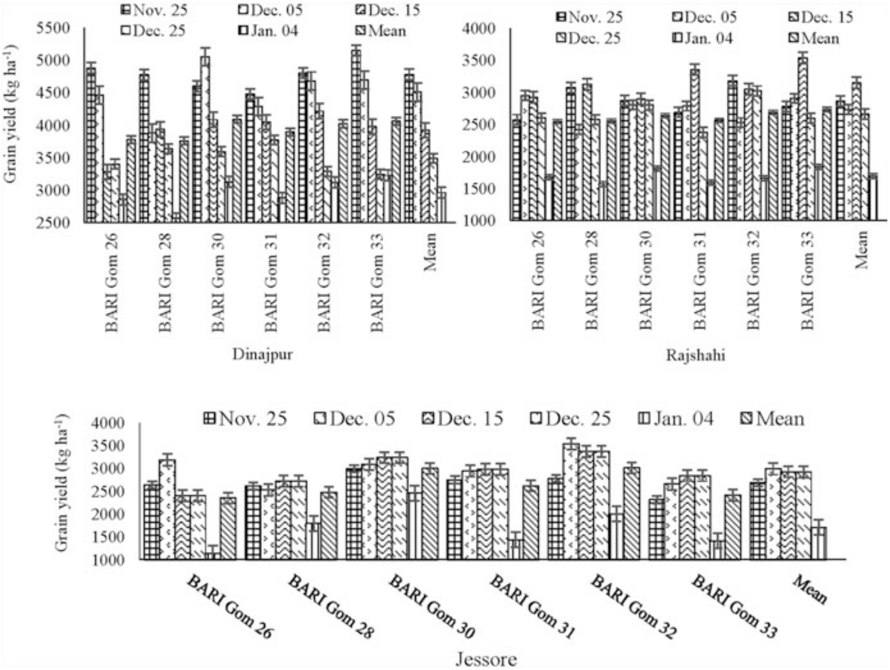

Fig. 11 Yield of wheat varieties is affected by sowing dates in Dinajpur, Rajshshi, and Jessore locations. Bars for yield of different wheat varieties are significantly different at $P \leq 0.05$ (LSD test). Mean ± SE in each bar was calculated from three replications for each treatment. (Adapted from Hossain et al. 2018b)

2016; Xie et al. 2016). However, farmers in Bangladesh are using a much higher seeding rate, sometimes even double the recommended rate, with the aim of controlling weeds, repelling birds, and achieving higher GY (Sarker et al. 2007). At the same time, wheat seeds are also considered to be an expensive input, and farmers often use low-quality and recycled seeds due to the high cost of seed from new and improved varieties (Sarker et al. 2009; Farooq et al. 2016). Considering the important issue, a seeding rate of 120 kg ha^{-1} was recommended by the Wheat Research Centre (WRC) in Bangladesh, irrespective of the variety, from the very initial stage of wheat introduction and expansion in Bangladesh (Razzaque et al. 2000; Islam et al. 2004), while Sarker et al. (2007) and Sarker et al. (2009) recommended that varieties with medium- to large-sized seed rate should 120 kg ha^{-1} and varieties with small seed rate should 100 kg ha^{-1}.

Recently, a field research was conducted in 2 consecutive years with five newly released wheat varieties ("BARI Gom 24," "BARI Gom 25," "BARI Gom 26," "BARI Gom 27," and "BARI Gom 28") to find out the optimum seeding rate for recently developed wheat varieties for reducing the production cost. Considerably maximum GY ($p \leq 0.05$) was obtained with a seeding rate of 140 kg ha^{-1} for all varieties, compared to other rates. A seeding rate less than the recommended rate

(120 kg ha^{-1}) for all varieties failed to produce comparable GY in both years. Among all varieties, “BARI Gom 26” had the highest GY, while “BARI Gom 25” had the lowest GY in both years. Since the combine effect of variety and seeding rate on GY did not vary significantly ($p \leq 0.05$) in both years, surplus GY was 467 and 233 kg ha^{-1}, respectively, for “BARI Gom 24,” 63 and 75 kg ha^{-1} for “BARI Gom 25,” 81 and 93 kg ha^{-1} for “BARI Gom 26,” 23 and 66 kg ha^{-1} for “BARI Gom 27,” and 152 and 220 kg ha^{-1} for “BARI Gom 28” in the first and second year when seeded at 140 kg ha^{-1}. For the same seed rate, the GY of “BARI Gom 24” increased by 5.3 to 9.6% and that of “BARI Gom 28” increased from 2.8 to 5% over the 2 years. Therefore, a seeding rate of 140 kg seed ha^{-1} is recommended for “BARI Gom 24” and “BARI Gom 28,” while the current recommended rate (120 kg ha^{-1}) should be continued for the other three varieties when grown under irrigation on the Old Himalayan Piedmont Plain of Bangladesh (Akhter et al. 2018; Table 17). Another 2-year research result also recommended

Table 17 Increase/decrease in yield (%) at 100 and 140 kg seed ha^{-1} compared to present recommended seeding rate (120 kg ha^{-1})

		Seed yield (kg ha^{-1})	% Increase/decrease in yield (kg ha^{-1})	Seed yield (kg ha^{-1})	% Increase/decrease in yield (kg ha^{-1})
Treatments		2013–14		2014–15	
Seeding rate (kg ha^{-1})					
100		5085	−147 (2.8%)	4279	−182 (4.1%)
120		5232	–	4461	–
140		5389	157 (3.0%)	4598	137 (3.07%)
F-test		**		**	
Variety x seeding rate interaction					
BARI Gom 24	100	4702	−170 (3.5%)	4180	−220 (5.0%)
	120	4872	–	4398	–
	140	5339	467 (9.6%)	4630	233 (5.3%)
BARI Gom 25	100	4688	−140 (2.9%)	4022	−110 (5.3%)
	120	4828	–	4128	–
	140	4891	63 (1.3%)	4203	75 (1.8%)
BARI Gom 26	100	5579	−80 (1.4%)	4450	−280 (4.7%)
	120	5656	–	4728	–
	140	5737	81 (1.4)	4820	93 (2.0%)
BARI Gom 27	100	5184	−260 (4.8%)	4427	−360 (4.8%)
	120	5436	–	4590	–
	140	5459	23 (0.2%)	4656	66 (1.4%)
BARI Gom 28	100	5270	−100 (1.9%)	4318	−140 (4.9%)
	120	5368	–	4460	–
	140	5520	152 (2.8%)	4680	220 (5.0%)
F-test		NS		NS	
CV (%)		3.10		3.52	

Adapted from Akhter et al. (2018)

seed rate at 140 kg ha^{-1} for newly released Zn-enriched blast-tolerant variety BARI Gom 33 (Jahan et al. 2018b).

8.3 Seeding with the Appropriate Machine for Reducing Production Cost

Agricultural mechanization has a significant contribution to agricultural development, and its purposes are increasing land and labor efficiency by reducing the difficulty in farming operation, bringing more lands under cultivation, and saving energy and resources. Since tillage is the basic operation in farming, in Bangladesh, traditionally land is highly fragmented; as a result, walking tractors are the major sources for field operations as these are much more productive than animal traction and become an economic alternative to small farming (Bill 1999; Hossain et al. 2002; Solomon 2017).

Wheat sowing period is very limited in Bangladesh due to a short period of winter. Late sowing is considered as a one of the key constraints for reducing the GY of wheat (Hossain et al. 2018b). On the other hand, tillage and sowing are costly, laborious, and time-consuming for wheat cultivation as after harvesting of T. *aman* (summer rice), farmers do not have enough time for land preparation with traditional bullock-driven plow. On the other hand, the availability of animal draft power is decreasing day by day. Normally, for conventional tillage, 10–22 days are required,

Fig. 12 Uniform seeding through power tiller operated seeder (PTOS)

because in conventional tillage take in 4–5 passes plow and then 10–12 times of laddering (Meisner et al. 1997). In case of power tiller seeder, tillage, seeding in line, laddering, and proper placement and delivery of seed and fertilizers into the soil could be done simultaneously (Ganesh 1999; Hossain et al. 2002; Rawson et al. 2007; Fig. 12). Hence, the farmers are becoming more dependent on mechanical power (Hossain et al. 2002). Nowadays, power tillers are existing in all over the country, and the most of the wheat farmers are using power tillers for wheat cultivation (Saunders 1991; Meisner 1996; Hossain et al. 2012).

The planter could get the power for a ground wheel for picking and delivering the wheat seeds. It could maintain the seed uniformly between rows to rows as well as seed to seed with similar depth. A uniform distribution of seed with 20 cm spacing along the row planting is desirable. The cup metering mechanism required to hold the seed in each cup should be between 12 and 15 seeds based on the physical property carried out to maintain the seed rate of 100 to 120 kg ha^{-1}, and the required plant population should be 350–380 plants m^{-2}, and it could place the seed 3–5 cm below the ground surface (Hossain et al. 2002; Solomon 2017). The planter (Fig. 13) consists of a cup feed metering mechanism, seed hopper, furrow opener, wheel, and shafts. The planter was designed to perform the following functions: (a) to carry the seeds, (b) to open furrow to the uniform depth, (c) to meter the seeds, (d) to place the seed in furrows in an acceptable pattern, and (e) to cover the seeds and compact the soil around the seed. A detailed description of a

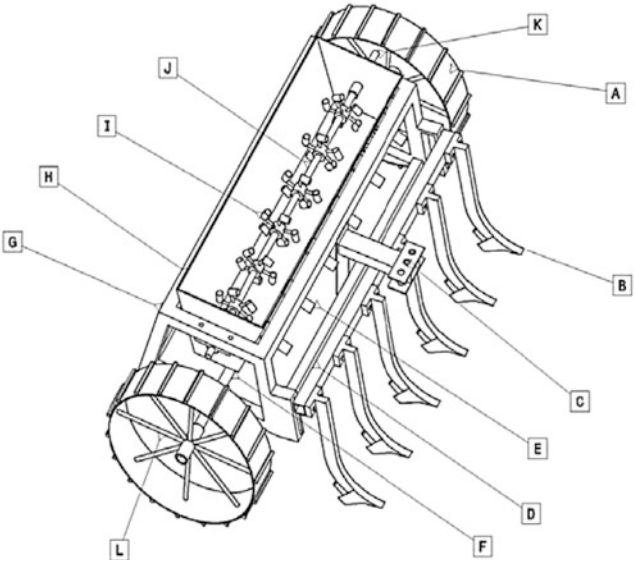

Fig. 13 Different parts of power tiller operated seeder: (**a**) ground drive wheel, (**b**) furrow openers and boot, (**c**) drawbar, (**d**) furrow opener frame, (**e**) seed outlet orifice, (**f**) wheel shaft, (**g**) frame, (**h**) hopper, (**i**) cup-type metering mechanism, (**j**) seed metering shaft, (**k**) chain and sprocket, and (**l**) spoke. (Adapted from Solomon 2017)

PTOS is as follows: (A) ground drive wheel, (B) furrow openers and boot, (C) drawbar, (D) furrow opener frame, (E) seed outlet orifice, (F) wheel shaft, (G) frame, (H) hopper, (I) cup-type metering mechanism, (J) seed metering shaft, (K) chain and sprocket, and (L) spoke (Solomon 2017; Fig. 13).

8.4 Seeding at Optimum Depth

The depth of seed sowing is an important management strategy that influences the development and stand establishment of plants that lead to influence the final grain yield of wheat (Taiz and Zeiger 2002; Akman and Topal 2013). Optimum sowing depth is thus the desired goal for seedling emergence and establishment of all crops. Optimum root systems can access greater soil profiles to absorb and accumulate more water and nutrients (Garnett et al. 2009). If seeds are sown at too shallow a depth, then sowing results in poor germination due to inadequate soil moisture in the top soil layer (Desbiolles 2002), while seeds sown at excessively deeper depths result in significantly reduced seedling emergence, crop establishment, and yield (Desbiolles 2002; Mohan et al. 2013).

Similar to a root system, coleoptile length in wheat is also positively correlated with growth and yield, and when seeds are sown too deep (9 cm), this can result in seedlings with a shorter coleoptile and a marked decline in yield (Yagmur and Kaydan 2009). Mohan et al. (2013) and Odeleye et al. (2007) noted that if seeds are placed deeper than the length of coleoptiles, then the shoot has to displace

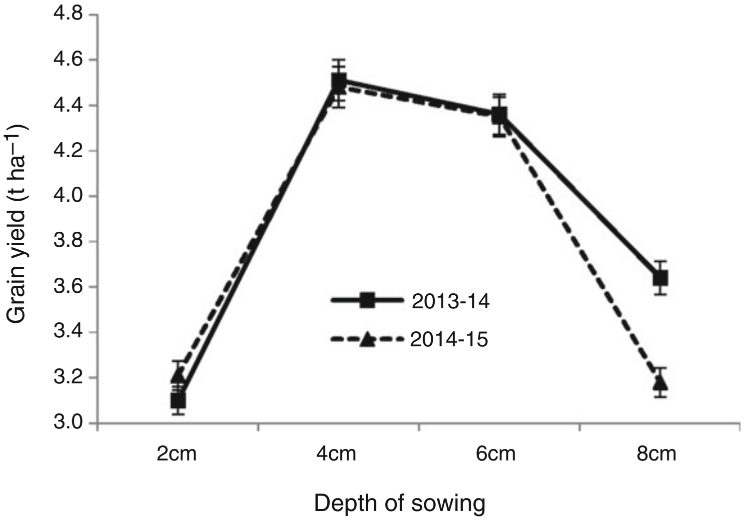

Fig. 14 Grain yield of wheat as affected by sowing depth. Mean (±SD) was calculated from three replicates for each treatment and significantly different at $P \leq 0.05$ (LSD test). (Adapted from Bazzaz et al. 2018)

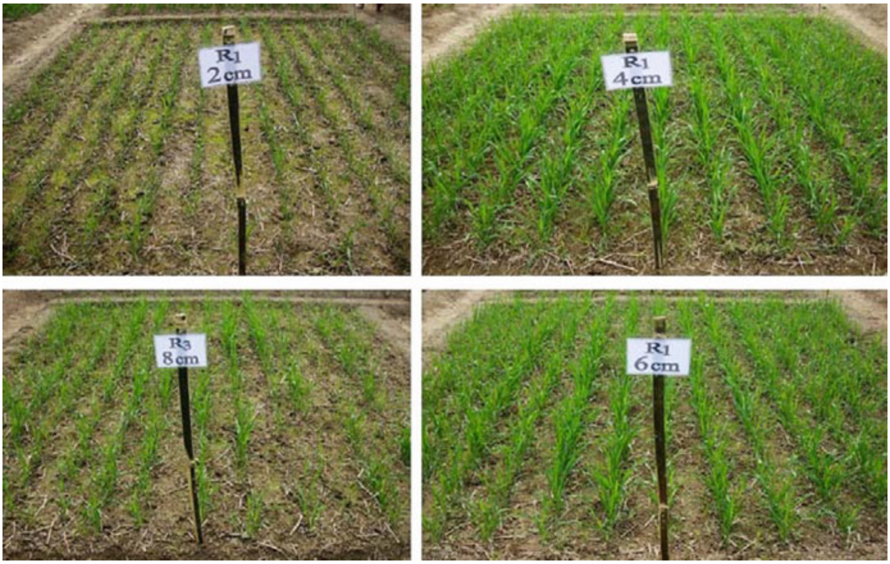

Fig. 15 Wheat seedling at different depths of sowing recorded at 25 DAS. (Adapted from Bazzaz et al. 2018)

superficial mechanical obstacles. The sowing depth for wheat has a continuous impact on spikes m^{-2} and finally on grain yield. Thus, a suitable depth of sowing is essential for emergence and successful crop production (Joshi et al. 2007; Rebetzke et al. 2007). Bazzaz et al. (2018; Figs. 14 and 15) revealed that optimum sowing depth for sandy and silty loam soils should be 4–6 cm for wheat seeding in Bangladesh.

8.5 Balance Fertilizer and Irrigation Management

Natural or synthetic origin of any material that supplies one or several essential nutrients for the growth and development of plants is called a fertilizer. Chemical fertilizers should include more than three essential elements; for example, NPK are considered the most significant plant nutrition. Secondary important chemical fertilizers should include the elements boron, sulfur, zinc, iron, magnesium, calcium, etc. (Mengel and Kirkby 1978). While manure and composts are known as organic fertilizers. It is estimated that 40–60% of all crop production fully depends on fertilizer application (Johnston and Bruulsema 2014). Hence, to secure future food demand under future changing climate, fertilizers could play a substantial role for the increasing population in the world. Environmentally friendly and to increase the fertilizer use efficiency, fertilizers should be used in a right source, right rate, right time, and right place (Mikkelsen 2011; Johnston and Bruulsema 2014; IPNI 2012, 2018).

In Bangladesh, 3000–4000 kg acre^{-1} (30–40 kg decimal^{-1}) cow dung is suggested to be applied before land preparation, whereas chemical fertilizers such as 100–27–40-20-1 kg ha^{-1} of N, P, K, S, and B are recommended to be applied for sustainable wheat production. To increase the fertilizers' use efficiency, 2/3 of nitrogen in combination with full quantity of other fertilizers should be applied as a basal during final land preparation. The remaining 1/3 N fertilizer should be applied immediately after the first irrigation (Bazzaz et al. 2018; Hossain et al. 2018a). First irrigation must be at 17–21 days after sowing (DAS); second and third irrigations must at booting (50–55 DAS) and grain filling (70–75 DAS) stages. Soils in the northern part of Bangladesh are acidic. Therefore it is recommended that if soil pH is 4.0 to 5.0, 800 kg acre^{-1} dolochun ($CaCO_3$) should be applied in moist soils at 7–10 days before sowing. If soil pH is 5.0 to 6.0, 400 kg acre^{-1} dolochun ($CaCO_3$) should be applied to reduce the soil acidity (Hossain et al. 2011).

8.6 Seed Treatment for Maximum Yield Through Accelerating Better Germination

The Bangladesh Wheat and Maize Research Institute (BWMRI) (earlier name, Wheat Research Center of Bangladesh Agricultural Research Institute) suggests to farmers for seeds treated with Provax-200 WP at 3 g fungicide kg^{-1} seed before sowing. This fungicide contains carboxin and thiram. For achieving excellent seed germination and for protecting fungal diseases in the soil of Bangladesh during the seedling stage, Provax-200 WP is an excellent fungicide (Hossain and Teixeira da Silva 2012). Germination of seed treating seeds were increased 20–22%, and ultimately increased the grain yield at 10–12% (Hossain and Teixeira da Silva 2012).

8.7 Weed Management

In Eastern Gangetic Plains (EGP) including Bangladesh, wheat area and production intensify day by day with high speed because of increasing demand for human consumption and food industries in the region. Presently wheat is grown more than 80% by manual sowing after intensive five to six tillage operations which delayed the wheat sowing at least 1–2 weeks. Late planting of wheat was identified as a higher weed infestation than optimum sowing. Therefore optimum time of sowing is important to overcome the weed infestation.

We can also overcome the problem through direct seeding immediately after rice harvest into the unbroken soil. A number of repetitive tillage operations increase the cost of cultivation and fuel consumption and delay planting in two ways: by repetitive tillage operations and by manual sowing. The traditional weed management in wheat after 30–35 days after seeding is that generally farmers cut the weeds with hand weeding which further consumed more labor. On the other hand, after seeding wheat growers face major challenges for weed management due to lack of pre- and postemergence herbicides in the wheat-growing areas of Bangladesh. Therefore, conservation agricultural (CA)-based new agronomic management practices are advocating to overcome these challenges. The zero−/strip-tilled wheat/permanent beds or till the soil with fresh beds is an alternate option through mechanized precision planting in a single pass. The CA-based crop management techniques face major concern of weed management initially.

Scientists of BWMRI are trying to find out appropriate weed management practices under CA-based system to overcome the weed infestation in a wheat field. In the context, a field research was carried out to assess the economic efficacy of different herbicides to control weed in wheat under zero-till and conventional tillage systems. Treatments were eight herbicides, one each weedy check and weed-free treatment (Table 18, Fig. 16). Considering the weed control efficiency, grain yield, and economic point of view, affinity and pinoxaden + metsulfuron were the best under strip tillage and conventional tillage system in Dinajpur location. In Rajshahi, it was pinoxaden + cartrazone both under the strip and conventional tillage system (Hossain et al. 2018c; Table 18 and Fig. 16).

8.8 Conservation Agricultural Practices

Nearly 85% of the area in the Indo-Gangetic Plain (IGP) of South Asia (including India, Pakistan, Nepal, and Bangladesh) followed intensive rice-wheat sequential irrigated cropping systems (Timsina and Connor 2001). As a result, productivity and fertility in the area are declining. To meet the food demand of increasing population, scientists are trying to introduce resource-conserving technologies (RCT) among the farmers. The farmers are also showing interest to grow a crop with RCT because it reduces cultivation cost, protects degrading soil, and saves water without any yield sacrifice. Also, RCT offers the opportunity to plant wheat timely. Delayed wheat planting reduces yield at 1.3% per day after Nov. 30. Due to scarcity and the high cost of labor and for reducing cultivation cost, RCT are essential for farming. Zero-till, bed planting strip tillage, and PTOS tillage options are known as RCT. However, for getting expected crop yields with RCT, a full package of production technologies especially fertilizer management should be provided. Broadcasting fertilizer enhances losses of fertilizer and reduces fertilizer use efficiency in RCT tillage options especially in zero-till and bed planting practices. On the other hand, there are many pieces of evidence that residue retention has a significant contribution to crop productivity and soil fertility with the sustainable way (Limon-Ortega et al. 2000; Singh et al. 2009a, b; Naresh et al. 2012). The work on residue management

Table 18 Weed control efficiency of different herbicides under two tillage system in both the locations

	Dinajpur		Rajshahi		Dinajpur		Rajshahi		Dinajpur		Rajshahi	
	Strip	Con.	Strip	Con.	Strip	Con.	Strip	Con.	Strip	Con.	Strip	Con.
Herbicides	% WCE of grass				% WCE of broadleaf				% WCE of sedge			
T1	20	25	53	48	57	43	45	21	5	46	33	19
T2	17	42	49	48	66	14	38	32	42	44	46	21
T3	44	44	39	49	31	20	46	9	26	43	44	24
T4	40	64	49	48	74	81	34	17	−7	36	51	20
T5	−14	39	55	50	64	49	36	26	3	37	44	10
T6	46	49	53	45	44	76	35	15	−25	42	41	21
T7	2	22	53	43	56	36	36	18	77	73	44	27
T8	1	37	56	38	64	3	35	17	81	78	49	34
T9	0	0	0	0	0	0	0	0	0	0	0	0
T10	62	54	55	47	63	43	28	18	73	54	52	17

Adapted from Hossain et al. (2018c)

WCE weed control efficiency, *Con.* conventional, *T1* ready-mix formulation (sulfosulfuron + metsulfuron) (trade name, Satasat), *T2* ready-mix formulation (mesosulfuron + idosulfuron) (trade name, Atlantis), *T3* pinoxaden (trade name, Axial), *T4* ready-mix formulation (carfentrazone + isoproturon) (Affinity, Bangladeshi), *T5* pinoxaden (Axial) + metsulfuron (Convo), *T6* pinoxaden (Axial) + carfentrazone (Affinity, Indian), *T7* halosulfuron (Sempra), *T8* halosulfuron (Sempra) + pinoxaden (Axial), *T9* weedy check, *T10* weed-free

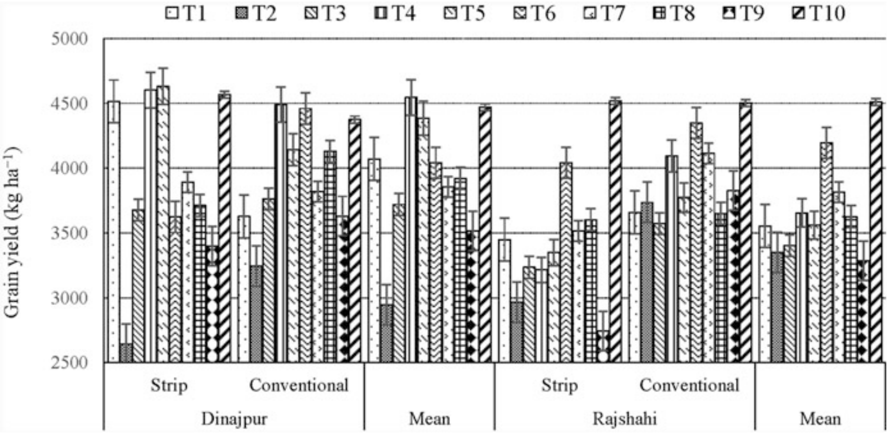

Fig. 16 Yield of wheat is influenced by herbicidal weed control methods under strip and conventional tillage system in two agroecological zones of Bangladesh. (Adapted from Hossain et al. (2018c)). *T1* ready-mix formulation (sulfosulfuron + metsulfuron) (trade name, Satasat), *T2* ready-mix formulation (mesosulfuron + idosulfuron) (trade name, Atlantis), *T3* pinoxaden (trade name: Axial), *T4* ready-mix formulation (carfentrazone + isoproturon) (Affinity, Bangladeshi), *T5* pinoxaden (Axial) + metsulfuron (Convo), *T6* pinoxaden (Axial) + carfentrazone (Affinity, Indian), *T7* halosulfuron (Sempra), *T8* halosulfuron (Sempra) + pinoxaden (Axial), *T9* weedy check; T10, weed-free

with RCT is rare in this country. So, scientists in the IGP are trying to find out the sustainable yield from the pattern and improve soil fertility and productivity.

8.9 Appropriate Wheat-Based Pattern

In Bangladesh, most of the wheat-growing farmers particularly in the northwestern part of Bangladesh are growing wheat in wheat-fallow-T. *aman* rice cropping pattern in the light soil for decades. Some farmers are growing wheat in wheat-jute-T. *aman* rice cropping pattern (Kabir and Islam 2012). There is the scope of introducing mung bean in the fallow period after wheat, and some farmers already started growing mung bean in *Kharif-I* after wheat. In some places of the northwestern part of Bangladesh, farmers are growing early potato before wheat sowing to earn more from the potato of the higher market price. For growing early potato, most of the lands remain fallow during Kharif II season due to lack of knowledge or short duration *aman* rice varieties (Kabir and Islam 2012). After wheat, farmers are growing maize or mung bean and then transplanted (T.) *aman* rice (Kabir and Islam 2012). Considering the important issue under changing climate, BWMRI of Bangladesh recommended some wheat-based cropping pattern after 4-year observation which is economically viable and environmentally friendly (Sarker et al. 2014).

Table 19 Wheat-based cropping pattern suitable for the light soil of northwestern part of Bangladesh

Cropping pattern 1																
Crops	**Potato**				**Maize**				***T. aman* rice**							
	2008–2009	2009–2010	2010–2011	2011–2012	2009	2010	2011	2012	2009	2010	2011	2012				
Variety	Granola	Granola	Diamant	Cardinal	Pacific 984	Pacific 984	Pacific 984	Pacific 984	BRRI 31	BRRI 49	BRRI 49	BRRI 49				
Yield (kg ha^{-1})	7037 (±510)	20,494 (±592)	36,794 (±962)	28,278 (±181)	8155 (±530)	8582 (±234)	12,332 (±261)	8776 (±202)	2960 (±145)	4373 (±181)	4741 (±340)	4953 (±223)				
Cropping pattern 2																
Crops	**Potato**				**Wheat**				**Mung bean**				**T. aman rice**			
	2008	2009	2010	2011	2008–2009	2009–2010	2010–2011	2011–2012	2009	2010	2011	2012	2009	2010	2011	2012
Variety	Granola	Granola	Granola	Granola	BARI 24	BARI 24	BARI 25	BARI 25	BARI 6	BARI 6	BARI 6	BARI 6	Bina 7	Bina 7	Bina 7	Bina 7
Yield (kg ha^{-1})	9660 (±479)	7631 (±208)	8393 (±576)	16,652 (±540)	3460 (±49)	3284 (±253)	4591 (±198)	3114 (±63)	552 (±97)	1454 (±261)	1323 (±38)	1152 (±119)	4175 (±56)	4362 (±372)	5214 (±209)	5387 (±97)
Cropping pattern 3																
Crops	**Wheat**				**Mung bean**				**T. aman rice**							
	2008–2009	2009–2010	2010–2011	2011–2012	2009	2010	2011	2012	2009	2010	2011	2012				
Variety	BARI 24	BARI 24	BARI 26	BARI 26	BARI 6	BARI 6	BARI 6	BARI 6	BRRI 31	BRRI 49	BRRI 49	BRRI 49				
Yield (kg ha^{-1})	4289 (±650)	4649 (±204)	4726 (±237)	5551 (±33)	615 (±110)	1506 (±152)	1411 (±147)	996 (±23)	4147 (±367)	4571 (±23)	5383 (±290)	5189 (±105)				
Cropping pattern 4																
Crops	**Wheat**				**T. aus rice**				**T. aman rice**							
	2008–2009	2009–2010	2010–2011	2011–2012	2009	2010	2011	2012	2009	2010	2011	2012				
Variety	BARI 24	BARI 24	BARI 26	BARI 26	BR 26	BR 26	BR 26	BR 26	BRRI 31	BRRI 49	BRRI 49	BRRI 49				
Yield (kg ha^{-1})	4247 (±116)	4780 (±227)	4383 (±45)	5737 (±78)	3149 (±96)	3229 (±26)	2941 (±214)	3041 (±93)	3260 (±133)	4369 (±256)	4793 (±301)	4740 (±115)				

(continued)

Table 19 (continued)

Cropping pattern 5																
Crops	**Wheat**				**Jute**				**T. aman rice**							
	2008–2009	2009–2010	2010–2011	2011–2012	2009	2010	2011	2012	2009	2010	2011	2012				
Variety	BARI 24	BARI 24	BARI 26	BARI 26	O 9897	O 9897	O 9897	O 9897	BRRI 31	BRRI 49	BRRI 49	BRRI 49				
Yield (kg ha^{-1})	3986 (±2)	4883 (±400)	4557 (±184)	5318 (±236)	2333 (±33)	2950 (±297)	2892 (±189)	3242 (±128)	3767 (±154)	4341 (±94)	4691 (±312)	4897 (±158)				
Cropping pattern 6																
Crops	**Potato**				**Wheat**				**Maize**				**T. Aman Rice**			
	2008	2009	2010	2011	2008–2009	2009–2010	2010–2011	2011–2012	2009	2010	2011	2012	2009	2010	2011	2012
Variety	Granola	Granola	Granola	Granola	BARI 24	BARI 24	BARI 25	BARI 25	Pacific 984	Pacific 984	Pacific 984	Pacific 984	Bina 7	Bina 7	Bina 7	Bina 7
Yield (kg ha^{-1})	10,525 (±638)	7701 (±449)	9494 (±275)	17,522 (±852)	3740 (±105)	3685 (±82)	4617 (±210)	3094 (±93)	5813 (±361)	9794 (±166)	9186 (±152)	7303 (±183)	3708 (±376)	4282 (±306)	4382 (±88)	5335 (±194)

Adapted from Sarker et al. (2014)

Figure in the parentheses indicates the standard error (±SE) of the mean

Among the wheat-based cropping pattern, early planted potato produced a lower yield, but it can accommodate a total of four crops in a cropping pattern with the higher gross return and gross margin. It was observed that a cropping pattern where potato was included gave the maximum benefit. Two four-crop-based cropping patterns, viz., potato-wheat-maize-T. *aman* rice and potato-wheat-mung bean-T. aman rice, with a three-crop cropping pattern (potato-maize-T. aman rice) are suitable for the light soil of the northwestern part of Bangladesh. Additionally, other two three-crop cropping patterns, viz., wheat-jute-T. aman rice and wheat-mung bean-T. aman rice, can be recommended for the region, especially for the marginal farmers (Sarker et al. 2014; Table 19).

8.10 Research Progress on Grain Quality of Wheat

Wheat area and its average production in Bangladesh are decreasing day by day, while demand is increasing due to increasing population. Food security is our first goal. Food security means sufficient food availability for the end user along with proper nutrition particularly fifth essential element zinc (Zn) for a human being. It is a vital micronutrient for the human body that takes part in many biological processes (Frassinetti et al. 2006). It is estimated that around 17% of the population across the globe are at risk of inadequate Zn intake and around 100,000 children who are younger than 5 years die every year due to Zn insufficiency (Bouis 2003; Lassi et al. 2016). WHO reported that Zn and Fe inadequacy is a serious health problem worldwide, and more than 3 billion people are faced in their deficiency (Graham et al. 2012).

Bio-fortification approach for proliferation of micronutrient concentration of staple foods through plant breeding can provide a rural-based, sustainable, and cost-effective intervention in combating micronutrient deficiency. Therefore, researchers are paying their attention to grow more food along with good nutrition especially bio-fortified or enrichment of Zn element. CIMMYT is working with national and international partners to invent and distribute bio-fortified wheat cultivars with vital yield and essential core traits. The first proof of concept results from the CIMMYT-derived high Zn lines tested in target environments which identified high Zn candidate varieties with durable resistance to rusts (Velu et al. 2012; Hao et al. 2014). There was hardly any correlation between grain Zn and grain yield, suggesting that enriched grain Zn can be combined in elite genetic backgrounds with no yield penalty (Velu et al. 2012). Identification of major QTLs attributing to high Zn would accelerate breeding efficiency. The objective of the study is to evaluate 50 Zn-enriched elite wheat lines developed by CIMMYT and to select suitable high-yielding genotypes along with the good agronomic background.

Considering the burning issue, the Bangladesh Wheat and Maize Research Institute (previous name, Wheat Research Centre of Bangladesh Agricultural Research Institute (BARI)) is working closely with CIMMYT to develop and deploy bio-fortified wheat varieties since 2013. As an output of the collaborative research, Bangladesh has released a bio-fortified wheat variety, namely, “BARI Gom 33” (before releasing, namely. “BAW 1260”), in 2017. It also possesses 2NS translocation which indicates a good level of tolerance against WB and is enriched with 50–55 ppm Zn.

8.11 Participatory Variety Selection (PVS)

BWMRI has released 33 varieties established by using conventional plant breeding tool, and many of these varieties have high-yield potential and tolerance against biotic and abiotic stresses. For quick dissemination of new varieties, every year BWMRI has been conducting more than 100s of demonstrations using new varieties through the Department of Agricultural Extension (DAE), NGOs, and scientists of BARI, providing different types of training (including the whole family) to thousands of wheat farmers, conducting farmers’ rallies, field days, workshops, etc. But this type of adoption is not good enough, although the technology transfer activities of BWMRI are quite good. This slow adoption was probably due to insufficient skill of the farmers about existing elite wheat varieties, lack of exactly improved varieties, selection of genotypes in the situations (research station trials) that does not suit well with the farmers’ field situation, etc.

By this time, participatory variety selection (PVS) has been found to be very effective in addressing many of these problems in many crops and countries of the world. PVS could be very useful to categorize farmers’ suitable new wheat cultivars, and thus farmers could overcome the constraints that cause by using old or outdated or stress-susceptible varieties (Joshi and Witcombe 1996; Pandit et al. 2011). In addition, production increases when farmers adopt new varieties through identification in PVS research (Witcombe 1999). Furthermore, PVS also increases the efficiency of the scientists (Bellon 2001) as well as farmers’ knowledge (Grisley and Shamambo 1993; Spearling and Loevinsohn 1993) for development of new wheat varieties. In the dissemination system, farmers directly participated during variety testing and selection process; as a result, adoption rates can be increased (Joshi et al. 1995). Keeping these in view, PVS research program has been undertaken, and all the varieties released since 1998 passed through participatory variety selection and so becoming popular among the farmers.

8.12 Variety Maintenance and Breeder Seed Production

Breeders take a small quantity of very pure seed stock upon release of a new variety. This stock represents a new variety as parental materials and also for future maintenance and seed multiplication (Laverack 1994). BWMRI maintenance breeding program is always trying extremely to maintain the purity of varieties and cultivars. A seed program capable of providing farmers with good-quality seed is essential to a nation's agricultural development (Johnson 1980), and seed is not just something planted by the farmers or companies; it is the carrier of the genetic potential for higher crop production (Dolouche and Potts 1971). Pure line theory is still one of the best conceptions for maintaining varietal purity of cereal crops. BWMRI maintenance breeding program had also been developed on the basis of the conception of pure line theory to preserve transparency as well as to produce the best quality of breeder seed in order to supply a handful amount to Bangladesh Agricultural Development Corporation (BADC) and some NGOs. Every year BWMRI produces about 60 ton breeders' seed of the commercial varieties and supplies to the registered seed growers.

9 International Linkages, Collaboration, and Policy Issues for Wheat Production in Bangladesh

CIMMYT has worked closely with BWMRI for promoting wheat cultivation in Bangladesh since the initial stage. It provided exclusive wheat germplasm to select genotypes, which are suitable to the environmental condition of Bangladesh. Many wheat scientists participated in training programmes at CIMMYT, Mexico, for wheat improvement, agronomic management, appropriate machinery, wheat seed quality, and conservation agriculture (Pandit et al. 2011) and also trained some BADC, DAE (Department of Agricultural Extension), NARS, and NGO personnel to improve the wheat seed production for the farmers of Bangladesh. It started from 1969 and continued.

In addition, BWMRI collaborates with CIMMYT, CIDA, AusAID, CSIRO and ACIAR, Australia, and USAID for improving the facility and development of manpower of the BWMRI in Bangladesh (Pandit et al. 2011). Recently, BWMRI has been researching in collaboration with CIMMYT, KSU, ACIAR, and USAID to develop blast-resistant wheat variety. Precision phenotyping platform (PPP) has been established at RARS Jessore with CIMMYT/ACIAR funding for large-scale screening of wheat blast. Few blast-resistant genotypes are also identified for further evaluation. A large number of germplasm received from CIMMYT have enriched our wheat genetic stock for proper evaluation and screening. This provides us the opportunity to select exotic genotypes against wheat blast and also adapted to our environmental conditions.

10 Future Strategies to Meet the Challenges of Changing Climate

- Harnessing genetic resources to accelerate breeding gains to address climate change issues.

- Development of high-yield potential and biotic and abiotic stress-resistant wheat varieties and having good end-use quality.
- Develop high-throughput phenotyping and genomic selection to identify useful alleles/traits for stress tolerance.
- Strategic deployment of traits/alleles into adapted genotypes with good agronomic background through MAS.
- Double haploid breeding and introduce speed breeding technology, bio-fortification, and nutritional improvement.
- Rapid multiplication of seeds of new wheat varieties.
- Short-, medium-, and long-term breeding plan to develop wheat blast-resistant variety.
- Improved crop management such as time of seeding, appropriate seed rate, sowing methods and sowing depth, balanced fertilizers, and irrigation management.
- Using resource conservation technology for improving fertility and productivity of soils in changing climate.
- Strengthen international collaboration and capacity development.

11 Conclusion and Outlook

In Bangladesh after rice, wheat is the second most important food grain. However, Bangladesh mostly depends on import to encounter the demand of wheat for the growing population. Its demand is increasing day by day, due to change in lifestyle and also increase in income and speedy urbanization. Therefore, it is imperative to increase the wheat production to ensure food security in the future of growing population. Wheat production in Bangladesh is facing many constraints such as terminal heat stress, drought, salinity, soil acidity, and many diseases. In addition, wheat also competes with different *rabi* crops during the wheat season. In the study, we tried to provide updated information on wheat research in Bangladesh in contracts with changing climate. This evidence and predictions from the study will provide wheat researchers to plan new breeding and other improved programs to mitigate food security in future under changing climate. The present chapter also tried to highlight what are the indicators for food security in the wider circumstance of South Asia, especially for a new emerging threat like wheat blast.

Acknowledgment We are so appreciative to all the editors and reviewers, for their good and informative commentaries and recommendations which have allowed us to make further perfections to the chapter. We also acknowledged the senior staffs of BWMRI, for their informative suggestions and comments while writing the chapter.

References

Ahmad F, Comeau A (1990) Wheat × pearl millet hybridization: consequence and potential. Euphytica 50:181–190

Ahmed SM (1986) An overview of wheat research and development in Bangladesh. 3rd national wheat training workshop. Wheat Research Center Bangladesh Agricultural Research Institute Dinajpur, August 4–5, 1986

Ahmed SM, Meisner C (1996) Wheat research and development in Bangladesh. Bangladesh Australia wheat improvement project and CIMMYT-Bangladesh; Published by Bangladesh Australia Wheat Improvement Project and CIMMYT-Bangladesh. https://libcatalog.cimmyt.org/Download/cim/66681.pdf. Accessed 29 Oct 2018

Akhter MM, Hossain A, Teixeira da Silva JA, Timsina J, Islam MS (2018) Growth and yield of five irrigated spring wheat genotypes as influenced by seed rate in old Himalayan Piedmont plain of Bangladesh. Songklanakarin J Sci Technol. Available online at: http://rdo.psu.ac.th/sjstweb/Ar-Press/61-Jan/18.pdf. (in press)

Akman H, Topal A (2013) Effects on wheat root growth and development of rhizosphere environment and stress factors. J Selcuk Univ Nat Appl Sci 26:824–838

Akram M, Ashraf MY, Ahmad R, Waraich EA, Iqbal J, Mohsan M (2010) Screening for salt tolerance in maize (*Zea mays* L.) hybrids at an early seedling stage. Pak J Bot 42(1):141–154

Alam K (2015) Farmers' adaptation to water scarcity in drought-prone environments: a case study of Rajshahi District, Bangladesh. Agric Water Manag 148:196–206

Alam KB, Shaheed MA, Ahmed AU, Malaker PK (1994) Bipolaris leaf Blight (spot blotch) of wheat in Bangladesh. In: Saunders DA, Hettel GP (eds) Wheat in heat-stressed environments: irrigated, dry areas and rice-wheat farming systems. CIMMYT, Mexico, pp 339–342

Alam MA, Kabir MR, Hakim MA, Mandal MSN, Hossain MM, Sarker MAZ, Sarker ZI, Barma NCD (2018) Genetic gain of wheat varieties in Bangladesh. In: WRC internal research review report 2017–18 (wheat breeding). Wheat Research Center, Bangladesh Agricultural Research Institute, Nashipur, Dinajpur

Alauddin M, Quiggin J (2008) Agricultural intensification, irrigation and the environment in South Asia: issues and policy options. Ecol Econ 65(1):111–124

Ashraf MY, Wu L (1994) Breeding for salinity tolerance in plants. Crit Rev Plant Sci 13(1):17–42

Barclay IR (1975) High frequencies of haploid production in wheat (*Triticum aestivum*) by chromosome elimination. Nature 256:410–411. https://doi.org/10.1038/256410a0

Barker R, Herdt RW, Rose B (1985) The rice economy of Asia. Resources for the future, Inc, The Johns Hopkins University Press, Washington, DC

Barma NCD (2018) An overview on variety development program of WRC. Presented in WRC Internal research review and planning workshop 2017–18, held on 15 July 2018 at BARI seminar room, BARI, Joydebpur Dhaka

Bazzaz MM, Hossain A, Timsina J, Teixeira da Silva JA, Nuruzzaman M (2018) Growth, yield attributes and yield of irrigated spring wheat as influenced by sowing depth. Open Agric 3:72–83. https://doi.org/10.1515/opag-2018-0008

BBS (2011) Handbook of agricultural statistics. Bangladesh Bureau of Statistics, Statistics and Informatics Division, Ministry of Planning, Dhaka

BBS (Bangladesh Bureau of Statistics) (2018) Statistical year book of Bangladesh. Dhaka: Statistics Division, Ministry of Planning, Government of Peoples Republic of Bangladesh, 2018, Dhaka

Bellon MR (2001) Participatory research methods for technology evaluation. A manual for scientist working with farmers. CIMMYT, Mexico, p 93

Bill AS (1999) Hand book of agricultural engineering, plant production engineering, vol 3. ASAE, Washington, DC

Borlaug NE (1970) Norman E Borlaug: the green revolution, peace and humanity: speech delivered upon receipt of the 1970 Nobel Prize, Oslo Norway, 1970. https://repository.cimmyt.org/handle/10883/19284. Accessed 29 Oct 2018

Bouis HE (2003) Micronutrient fortification of plants through plant breeding: can it improve nutrition in man at low cost? Proc Nutr Soc 62(2):403–411

Braun H-J, Atlin G, Payne T (2010) Multi-location testing as a tool to identify plant response to global climate change. In: Reynlods MP (ed) Climate change & crop production. CABI International, Oxfordshire, pp 115–138

Byerlee D, Siddiq A (1994) Has the green revolution been sustained? The quantitative impact of the seed-fertilizer revolution in Pakistan revisited. World Dev 22(9):1345–1361

Callaway E (2016) Devastating wheat fungus appears in Asia for the first time. Nature 532:421–422

Ceresini PC, Castroagudín VL, Rodrigues FÁ, Rios JA, Aucique-Pérez CE, Moreira SI, Croll D, Alves E, de Carvalho G, Maciel JL, McDonald BA (2018) Wheat blast: from its origins in South America to its emergence as a global threat. Mol Plant Pathol. https://doi.org/10.1111/mpp.12747

Chauhdary JN, Khan UD, Shah SH, Shahid MA, Arsalan M (2016) Effect of sowing methods and seed rates on wheat yield and water productivity. Qual Assur Saf Crops Foods 8:267–272

Chowdhury AK, Saharan MS, Aggrawal R, Malaker PK, Barma NC, Tiwari TP, Duveiller E, Singh PK, Srivastava AK, Sonder K, Singh RP (2017) Occurrence of wheat blast in Bangladesh and its implications for South Asian wheat production. Indian J Genet Plant Breed 77(1):1–9

CIMMYT (International Maize and Wheat Improvement Center) (2015) Field demonstration of the impact of the use of machinery on wheat production in Faridpur, Bangladesh. Unpublished data from field demonstration in Faridpur, CIMMYT, Dhaka, Bangladesh

Cruz CD, Peterson GL, Bockus WW, Kankanala P, Dubcovsky J, Jordan KW, Akhunov E, Chumley F, Baldelomar FD, Valent B (2016) The 2NS translocation from *Aegilops ventricosa* confers resistance to the *Triticum* pathotype of *Magnaporthe oryzae*. Crop Sci 56(3):990–1000

Deaton A, Dreze J (2009) Food and nutrition in India: facts and interpretations. Econ Polit Wkly 44 (7):42–65

Desbiolles J (2002) Optimising seeding depth in the paddock, 2002. http://www.unisa.edu.au/amrdc/Areas/Proj/SeedTrials/Seeding_depth_article_Kerribee.pdf. Accessed 29 Oct 2018

Dey NC, Bala SK, Islam AKM S, Rashid MA, Hossain M (2013) Sustainability of groundwater use for irrigation in Northwest Bangladesh, Dhaka. National Food Policy Capacity Strengthening Programme (NFPCSP) and BRAC, Bangladesh. http://www.nfpcsp.org/agridrupal/sites/default/files/ToR-2.pdf. Accessed 29 Oct 2018

Dolouche JC, Potts HC (1971) Seed program development. Mississippi State University, State College

Duveiller E, Gilchrist L (1994) Production constraints due to *Bipolaris sorokiniana* in wheat: current situation and future prospects. In: Saunders DA, Hettel GP (eds) Wheat in heat-stressed environments: irrigated, dry areas and rice-wheat farming systems. Mexico, CIMMYT, pp 343–352

Duveiller E, Kandel YR, Sharma RC, Shrestha SM (2005) Epidemiology of foliar blights (spot blotch and tan spot) of wheat in the plains bordering the Himalayas. Phytopathology 5 (3):248–256

Eckardt NA (2010) Evolution of domesticated bread wheat. Plant Cell 22(4):993. https://doi.org/10.1105/tpc.110.220410

Fahad S, Hussain S, Matloob A, Khan FA, Khaliq A, Saud S, Hassan S, Shan D, Khan F, Ullah N, Faiq M (2015) Phytohormones and plant responses to salinity stress: a review. Plant Growth Regul 75(2):391–404

FAO (Food and Agriculture Organization of the United Nations) (2018a) Maize, rice, wheat farming must become more sustainable. FAO, Rome. http://www.fao.org/news/story/en/item/273303/icode/. Accessed 18 July 2018

FAO (Food and Agriculture Organization of the United Nations) (2018b) Data domain: production: crops. FAO, Rome. http://www.fao.org/faostat/en/#data/QC. Accessed 18 July 2018

Farooq M, Bramley H, Palta JA, Siddique KH (2011) Heat stress in wheat during reproductive and grain-filling phases. Crit Rev Plant Sci 30:491–507. https://doi.org/10.1080/07352689.2011.615687

Farooq U, Khan EA, Khakwani AA, Ahmed S, Ahmed N, Zaman G (2016) Impact of sowing time and seeding density on grain yield of wheat variety Gomal-08. Asian J Argic Biol Yield 4 (2):38–44

Flavell RB (1981) An overview of plant genetic engineering in crop improvement. A Rockefeller foundation conference, USA, pp 3–11

Frassinetti S, Bronzetti G, Caltavuturo L, Cini M, Croce CD (2006) The role of zinc in life: a review. J Environ Pathol Toxicol Oncol 25(3):597–610

Gandhi VP, Zhou Z, Mullen J (2004) India's wheat economy: will demand be a constraint or supply. Econ Polit Wkly 39:4737–4746

Ganesh S (1999) Performance evaluation of different seed drill in farmers. Fields annual report FY 2056/57, Agricultural Implement Research Centre. Ranighat, Birganj, Nepal

Garnett T, Conn V, Kaiser BN (2009) Root based approaches to improving nitrogen use efficiency in plants. Plant Cell Environ 32:1272–1283

Goswami BK, Kader KA, Malaker PK, Faruq MI (2004) Major diseases of wheat and maize and their control (in Bengali). Publication No bklt-02/2004-05, Published by Plant Pathology Division, BARI, Joydebpur, Gazipur-1701

Government of India (2016) Minutes of the meeting on "Occurrence of blast disease on wheat" held under the chairmanship of agriculture commissioner on 28th September, 2016 at Kolkata. File no. 4–2/20 13-NFSM (Ministry of Agriculture & Farmers Welfare Department of Agriculture Cooperation & Farmers Welfare Crops Division NFSM Cell, ed.). Krishi Bhawan, New Delhi, p 14

Grisley W, Shamambo M (1993) An analysis of adoption and diffusion of Carioca beans in Zambia resulting from an experimental distribution of seed. Exp Agric 29:379–386

Graham RD, Knez M, Welch RM (2012) How much nutritional iron deficiency in humans globally is due to an underlying zinc deficiency? In: Advances in agronomy 2012 Jan 1, vol 115. Academic Press, pp 1–40. https://doi.org/10.1016/B978-0-12-394276-0.00001-9

Hakim MA, Hossain A, Teixeira da Silva JA, Zvolinsky VP, Khan MM (2012) Yield, protein and starch content of twenty Wheat (*Triticum aestivum* L.) genotypes exposed to high temperature under late sowing conditions. J Sci Res 4(2):477–489

Hao Y, Velu G, Peña RJ, Singh S, Singh RP (2014) Genetic loci associated with high grain zinc concentration and pleiotropic effect on kernel weight in wheat (*Triticum aestivum* L.). Mol Breed 34(4):1893–1902

Hossain M (1998) Sustaining food security in Asia: economic, social, and political aspects. In: Dowling NG, Greenfield SM, Fischer KS (eds) Sustainability of rice in the global food system. International Rice Research Institute, Los Baños

Hossain A, Teixeira da Silva JA (2012) Phenology, growth and yield of three wheat (*Triticum aestivum* L.) varieties as affected by high temperature stress. Not Sci Biol 4(3):97–106

Hossain A, Teixeira da Silva JA (2013) Wheat production in Bangladesh: its future in the light of global warming. AoB Plants 5:pls042. https://doi.org/10.1093/aobpla/pls042

Hossain MI, Meisner CA, Sufian MA, Rashid MH, Amin MR (2002) Performance of power tiller operated seeder for wheat cultivation. Bangladesh J Agric Res 27(3):393–400

Hossain A, Sarker MAZ, Hakim MA, Islam MT, Ali ME (2011) Effect of Lime, magnesium and Boron on wheat (*Triticum aestivum* L.) and their residual effect on mungbean (*Vigna radiata* L.). Int J Agric Res Innov Technol 1(1&2):44–54

Hossain MI, Hossain I, Mamun MA, Siddiquie NA, Rahman MM, Rahman MS (2012) Two wheel tractor operated strip tillage seeding equipment for dry land farming. Int J Energy Mach 5 (1):35–41

Hossain A, Sarker MAZ, Saifuzzaman M, Teixeira da Silva JA, Lozovskaya MV, Akhter MM (2013) Evaluation of growth, yield, relative performance and heat susceptibility of eight wheat (*Triticum aestivum* L.) genotypes grown under heat stress. Int J Plant Prod 7(3):615–636

Hossain MM, Hossain A, Alam MA, Sabagh AEL, Murad KFI, Haque MM, Muriruzzaman M, Islam MZ, Das S (2018a) Evaluation of fifty irrigated spring wheat genotypes grown under late sown heat stress condition in multiple environments of Bangladesh. Fresenius Environ Bull 27 (9):5993–6004

Hossain A, Hossain MI, Sarker MAZ, Bazzaz M, Barma NCD, Krupnik T (2018b) Response of newly evolved wheat genotypes to sowing dates. WRC internal research review report 2017–18 (Crop management). Wheat Research Center, Bangladesh Agricultural Research Institute, Nashipur, Dinajpur-5200, Bangladesh

Hossain A, Hossain MI, Sarker MAZ, Bazzaz M, Barma NCD, Gathala MK (2018c) Wheat management options for zero and conventional tillage wheat. WRC internal research review report 2017–18 (Crop management). Wheat Research Center, Bangladesh Agricultural Research Institute, Nashipur, Dinajpur-5200, Bangladesh

Huang B (1996) Gametoclonal variation in crop improvement. In: Jain SM, Sopory SK, Veilleux RE (eds) In vitro haploid production in higher plants, vol 2. Kluwer, Dordrecht, pp 73–91

Huq S (2006) Learning to live with climate change. International Institute for Environment and Development (IIED), London

Hussain S, Jamil M, Napar AA, Rahman R, Bano A, Afzal F, Kazi AG, Mujeeb-Kazi A (2016) Heat stress in wheat and interdisciplinary approaches for yield maximization. In: Azooz MM, Ahmad P (eds) Plant-environment interaction: responses and approaches to mitigate stress. Wiley, Chichester. https://doi.org/10.1002/9781119081005.ch9

Inagaki MN, Mujeeb-Kazi A (1995) Comparison of polyhaploid production frequencies in crosses of hexaploid wheat with maize, pearl millet and sorghum. Breed Sci 45:157–161

Index Mundi (2018) Bangladesh wheat production by year: Market year, production (1000MT) and growth rate (%).. http://www.indexmundi.com/agriculture/?country=bd&commodity=wheat&graph=production. Accessed 4 May 2018

IPCC (Intergovernmental Panel on Climate Change) (2007) Climate change 2007. Synthesis report. In: Pachauri RK, Reisinger AJ (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, p 104. https://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch10s10-4-1.html. Accessed 15 Aug 2018

IPNI (International Plant Nutrition Institute) (2012) In: Bruulsema TW, Fixen PE, Sulewski GD (eds) 4R plant nutrition manual: a manual for improving the management of plant nutrition, metric version. International Plant Nutrition Institute, Norcross

IPNI (International Plant Nutrition Institute) (International Plant Nutrition Institute) (2018) History of the “4Rs”. http://www.ipni.net/ipniweb/portal/4r.nsf/article/4r-history. Accessed 29 Oct 2018

Iqbal N, Akbar N, Ali M, Sattar M, Ali L (2010) Effect of seed rate and row spacing on yield and yield components of wheat (*Triticum aestivum* L). J Agric Res 48:151–156

Islam AS (2008) Analyzing changes of temperature over Bangladesh due to global warming using historic data. Young Scientists of Asia Conclave, Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), 15–17 January, Jakkur, Bangalore

Islam MS, Sattar MA, Rahman MM, Qayyum MA, Alam SMN, Alam M S, Mustafi RA (2004) Krishi Proiukti Hatboi (Handbook on Agro-Technol grain yield),) 3rd edn, Bangladesh Agricultural Research Institute, Gazipur 1701, Bangladesh, pp l–560. (In Bangla)

Islam MT, Croll D, Gladieux P, Soanes DM, Persoons A, Bhattacharjee P, Hossain MS, Gupta DR, Rahman MM, Mahboob MG, Cook N, Salam MU, Surovy MZ, Sancho VB, Maciel JLN, Nhani AJ, Castroagudín VL, de Assis Reges JT, Ceresini PC, Ravel S, Kellner R, Fournier E, Tharreau D, Lebrun MH, McDonald BA, Stitt T, Swan D, Talbot NJ, Saunders DGO, Win J, Kamoun S (2016) Emergence of wheat blast in Bangladesh was caused by a South American lineage of *Magnaporthe oryzae*. BMC Biol 14:84. https://doi.org/10.1186/s12915-016-0309-7

Jahan MAHS, Hossain A, Timsina J, Teixeira da Silva JA (2018a) Evaluation of six irrigated spring wheat (*Triticum aestivum* L.) genotypes tolerant to heat stress using stress tolerance indices and correlation analysis. Int J Agric Res 13(1):39–52. https://doi.org/10.3923/ijar.2018

Jahan MAHS, Hossain A, Bazzaz M, Alam MM, Ali MA, Barma NCD (2018b) Adjustment of seed rate for Zn enriched wheat variety BAR Gom 33. WRC internal research review report 2017–18 (Crop Management). Wheat Research Center, Bangladesh Agricultural Research Institute, Nashipur, Dinajpur-5200, Bangladesh

Johnson ED (1980) Successful seed program: a planning and management guide. A book. Westview Press Inc Boulder, Colorado, p 9

Johnston AM, Bruulsema TW (2014) 4R nutrient stewardship for improved nutrient use efficiency. Proc Eng 83:365–370. https://doi.org/10.1016/j.proeng.2014.09.029

Joshi A, Witcombe JR (1996) Farmer participatory crop improvement. II. Participatory varietal selection: a case study in India. Exp Agric 32:461–477

Joshi KD, Rana RB, Subedi M, Kadayat KB, Sthapit BR (1995) Effectiveness of participatory testing and dissemination programme: a case study of Chaite Rice in the Western Hills of Nepal. LARC working paper No. 95/49, Lumble Agricultural Research Centre, Pokhara, Nepal

Joshi AK, Chand R, Arun B, Singh RP, Ortiz R (2007) Breeding crops for reduced-tillage management in the intensive, rice–wheat systems of South Asia. Euphytica 153(1–2):135–151

Kabir MJ, Islam M (2012) Study on agronomically and economically dominant cropping patterns in some selected areas of Barisal district. Bangladesh J Agric Res 37(1):55–65

Karim Z (1993) Preliminary agricultural vulnerability assessment: drought impacts due to climate change in Bangladesh. IPCC Eastern Hemisphere workshop on vulnerability assessment to sea-level rise and coastal zone management, Tsukuba, Japan, 3–6 August 1993

Karim Z, Hossain SG, Ahmed M (1990) Salinity problems and crop intensification in the coastal region of Bangladesh. Soil publication no 33, BARC, p 63

Khan MA, Yasmin S, Ansari R, Shirazi MU, Ashraf MY (2007) Screening for salt tolerance in wheat genotypes at an early seedling stage. Pak J Bot 39(7):2501–2509

Khan MM, Khan MSI, Mondal RS, Rashid MH, Faruq G, Rahman MM, Barma NCD (2018) Performance of some selected wheat genotypes in southern Bangladesh. WRC Internal Research Review Report 2017–18 (Crop Management). Wheat Research Center, Bangladesh Agricultural Research Institute, Nashipur, Dinajpur-5200, Bangladesh

Kohli MM, Mehta YR, Guzman E, De Viedma L, Cubilla LE (2011) Pyricularia blast – a threat to wheat cultivation. Czech J Genet Plant Breed 47:130–134

Kumar P, Mruthyunjaya, Dey MM (2007) Long-term changes in Indian food basket and nutrition. Econ Polit Wkly 42(35):3567–3572

Laghari GM, Oad FC, Tunio S, Chachar Q, Ghandahi AW, Siddiqui MH, Hassan SW, Ali A (2010) Growth and yield attributes of wheat at different seed rates. Sarhad J Agric 27(2):177–183

Lagos JE, Hossain T (2016) Bangladesh: grain and feed annual. GAIN ReportBG6005. United States Department of Agriculture (USDA), Foreign Agricultural Service, Washington DC. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Dhaka_Bangladesh_3-31-2016.pdf. Accessed 29 Oct 2018

Lassi ZS, Moin A, Bhutta ZA (2016) Zinc supplementation for the prevention of pneumonia in children aged 2 months to 59 months. The Cochrane Library, 1 Jan 2016

Laurie DA, Bennett MD (1988) The production of haploid plants from wheat x maize crosses. Theor Appl Genet 76:393–397

Laverack GK (1994) Management of breeders' seed production. Seed Sci Technol 22:551–563

Leite LF, Madari BE (2011) Soil organic matter: Brazilian perspectives. Dyn Soil Dyn Plant 5 (Special Issue 1):1–6

Li Y, Cui Z, Ni Y, Zheng M, Yang D, Jin M, Chen J, Wang Z, Yin Y (2016) Plant density effect on grain number and weight of two winter wheat cultivars at different spikelet and grain positions. PLoS One 11(5):e0155351. https://doi.org/10.1371/journal.pone.0155351

Limon-Ortega AL, Sayre KD, Francis CA (2000) Wheat nitrogen use efficiency in a bed planting system in Northwest Mexico. Agron J 92:303–308

Ma H, Busch RH, Riera-Lizarazu O, Rines HW (1999) Agronomic performance of lines derived from anther culture, maize pollination and single-seed descent in a spring wheat cross. Theor Appl Genet 99:432–436

Malaker PK, Barma NCD, Tiwari TP, Collis WJ, Duveiller E, Singh PK, Joshi AK, Singh RP, Braun HJ, Peterson GL, Pedley KF, Farman ML, Valent B (2016) First report of wheat blast caused by *Magnaporthe oryzae* pathotype *triticum* in Bangladesh. Plant Dis 100:2330. https://doi.org/10.1094/PDIS-05-16-0666-PDN

Mason NM, Jayne TS, Shiferaw B (2015) Africa's rising demand for wheat: trends, drivers, and policy implications. Dev Policy Rev 33(5):581–613

McDonald BA, Stukenbrock EH (2016) Rapid emergence of pathogens in agro-ecosystems: global threats to agricultural sustainability and food security. Philos Trans R Soc B 371:1–9

Meisner CA (1996) Report of 11n on-farm survey of the greater Comilla region: wheat growers' practices, perceptions, and their implications. Monograph No 13, BARI, Wheat Research Centre, BARI, Nashipur, Dinajpur

Meisner CA, Hobbs P, Badaruddin M, Razzaque MA, Giri GS, Justice S (1997) Mechanical revolution among small landholders of South Asia: the growing use of Chinese hand tractors. Joiru International conference on agricultural engineering and technology. Exhibition 97, Dhaka, Bangladesh, pp 781–787

Mengel K, Kirkby EA (1978) Principles of plant nutrition, p 593. https://www.cabdirect.org/cabdirect/abstract/19780649166. Accessed 29 Oct 2018

Mikkelsen RL (2011) The "4R" nutrient stewardship framework for horticulture. HortTechnology 21(6):658–662

Mittal S (2007) What affects changes in cereal consumption? Econ Polit Wkly 42(5):444–447

Mohan A, Schillinger WF, Gill KS (2013) Wheat seedling emergence from deep planting depths and its relationship with coleoptile length. PLoS One 8(9):e73314. https://doi.org/10.1371/journal.pone.0073314

Morris ML, Chowdhury N, Meisner C (1997) Wheat production in Bangladesh: technological, economic and policy issues. IFPRI Research Report No 106. International Food Policy Research Institute (IFPRI), Washington, DC

Mottaleb KA, Rahut DB, Kruseman G, Erenstein O (2018a) Wheat production and consumption dynamics in an Asian rice economy- the Bangladesh case. Eur J Dev Res 30(2):252–275

Mottaleb KA, Rahut DB, Kruseman G, Erenstein O (2018b) Changing food consumption of households in developing countries: a Bangladesh case. J Int Food Agribus Market 30 (2):156–174

Mottaleb KA, Rahut DB, Kruseman G, Erenstein O (2018c) Evolving food consumption patterns of rural and urban households in developing countries: a Bangladesh case. Br Food J 20 (2):392–408

Mottaleb KA, Singh PK, Sonder K, Kruseman G, Tiwari TP, Barma NCD, Malaker PK, Braun H-J, Erenstein O (2018d) Threats of wheat blast to South Asia's food security: an *ex-ante* analysis. PLoS One 13:e0197555. https://doi.org/10.1371/journal.pone.0197555

Naresh RK, Singh SP, Chauhan P (2012) Influence of conservation agriculture, permanent raised bed planting and residue management on soil quality and productivity in maize–wheat system in western Uttar Pradesh. Int J Life Sci Biotechnol Pharma Res 1:27–34

Nghiep HV, Gaur A (2005) Efficacy of seed treatment in improving seed quality in rice (*Oryza sativa* L.). Omonrice 13:42–51

Odeleye FO, Odeleye OMO, Olaleye AO, Yakubu FB (2007) Effect of sowing depth on emergence, growth and yield of okra (*Abelmoschus esculentus* (L.) Moench). J Food Agric Environ 5 (1):205–209

Pandit DB, Mandal MSN, Hakim MA, Barma NCD, Tiwari TP, Joshi AK (2011) Farmers' preference and informal seed dissemination of first Ug99 tolerant wheat variety in Bangladesh. Czech J Genet Plant Breed 47(Special Issue):160–164

Parida AK, Das AB (2005) Salt tolerance and salinity effects on plants: a review. Ecotoxicol Environ Saf 60(3):324–349

Pingali P (2007) Westernization of Asian diets and the transformation of food systems: implications for research and policy. Food Policy 32(3):281–298

Press Trust of India (2017) Deadly wheat blast disease spreads to Bengal districts. In: Joshi V (ed) The New Indian Express. Express Publications (Madurai) Limited, Chennai

Pretorius ZA, Singh RP, Wagoire WW, Payne TS (2000) Detection of virulence to wheat stem rust resistance gene Sr31 in *Puccinia graminis* f. sp. tritici in Uganda. Plant Dis 84:203

Rahman MM, Ahsan M (2001) Salinity constraints and agricultural productivity in coastal saline area of Bangladesh. Soil resources in Bangladesh: assessment and utilization, vol 1. Soil Resources Development Institute, Dhaka, pp 1–4

Raina SK (1997) Doubled haploid breeding in cereals. In: Janick J (ed) Plant breeding reviews, vol 15. Wiley, New York, pp 141–186

Rao CHH (2000) Declining demand for food grains in rural India: causes and implications. Econ Polit Wkly 35(4):201–206

Rawson HM, Gomez-Macpherson H, Hossain AB, Saifuzzaman M, Rashid H, Sufian MA, Samad MA, Sarker AZ, Ahmed F, Talukder ZI, Rahman M (2007) On-farm wheat trials in Bangladesh: a study to reduce perceived constraints to yield in traditional wheat areas and southern lands that remain fallow during the dry season. Exp Agric 43(1):21–40

Rawson HM (ed) (2011) Sustainable intensification of Rabi cropping in southern Bangladesh using wheat and mungbean, ACIAR technical reports no. 78. Australian Centre for International Agricultural Research, Canberra. 256 pp. https://www.aciar.gov.au/node/10506

Razzaque MA, Sattar MA, Amin MS, Qayyum MA, Alam MS (eds) (2000) *Krishi Projukti Hatboi* (Handbook on Agro-technolograin yield) 2nd edn, Bangladesh Agricultural Research Institute, Gazipur 170 Bangladesh, pp 1–464. (In Bangla)

Rebetzke GJ, Richards RA, Fettell NA, Long MA, Condon G, Forrester RI, Botwright TL (2007) Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. Field Crop Res 100:10–23

Reis EM (1991) Integrated disease management: the changing concepts of controlling head blight and spot blotch. In: Saunders DA (ed) Wheat in heat stressed environments: irrigated, dry areas and ricewheat systems. CIMMYT, Mexico, pp 165–177

Reza MMA, Malaker PK, Hossain MM, Rahman MME, Mustarin K, Anwar B, Roy KK (2018) Research report on disease management 2017–18. Plant pathology division, wheat research centre, BARI, Dinajpur, Bangladesh. Presented in the internal review and programme planning workshop, held on 15–17 July, BARI, Joydebpur, Dhaka

Sadat MD, Choi J (2017) Wheat blast: a new fungal inhabitant to Bangladesh threatening world wheat production. Plant Pathol J 33:103–108

Saharan MS, Bhardwaj SC, Chatrath R, Sharma P, Choudhary AK, Gupta RK (2016) Wheat blast disease—an overview. J Wheat Res 8:1–5

Sarker MAZ, Malaker PK, Saifuzzaman M, Pandit DB (2007) Effect of variety and seed rate on the yield of wheat. Bangladesh J Agric Environ 3(1):75–82

Sarker MAZ, Malaker PK, Bodruzzaman M, Barma NCD (2009) Effect of management and seed rate on the performance of wheat varieties with varying seed sizes. Bangladesh J Agric Res 34 (3):481–492

Sarker MA, Itohara Y, Hoque M, Uddin SN (2011) Scope and challenges of organic wheat cultivation in Bangladesh. Aust J Crop Sci 5(9):1114–1119

Sarker MAZ, Alam MA, Hossain A, Mannaf MA (2014) Agro-economic performance of crop diversification in rice based cropping systems of Northwest Bangladesh. Agric For Fish 3 (4):264–270. https://doi.org/10.11648/j.aff.20140304.18

Saunders I (1991) Report of an on-farm survey of the Jessore and Kustia Districts: wheat farmers' practices and their perceptions. Monograph no 8, BARI, Wheat Research Center, Nashipur, Dinajpur, Bangladesh

Selvaraju R, Subbiah AR, Baas S, Juergens I (2006) Livelihood adaptation to climate variability and change in drought prone areas of Bangladesh: developing institutions and options. Asian Disaster Preparedness Centre, Food and Agriculture Organization of the United Nations, Rome

Sen A (1981) Poverty and famines: an essay on entitlement and deprivation. Oxford University Press, Oxford

Shamsudduha M, Chandler RE, Taylor RG, Ahmed KM (2009) Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna delta. Hydrol Earth Syst Sci 13:2373–2385

Sharma R (2017) Wheat blast research: status and imperatives. Afr J Agric Res 12:377–381

Singh RP, Huerta-Espino J, Roelfs AP (2002) The wheat rusts. In: Curtis BC, Rajaram S, Macpherson HG (eds) Bread wheat: improvement and production, Plant Production and Protection Series, no 30. FAO, Rome, pp 227–249

Singh RP, Hodson DP, Huerta-Espino J, Jin Y, Njau P, Wanyera R, Herrera-Foessel SA, Ward RW (2008) Will stem rust destroy the world's wheat crop? Adv Agron 98:271–309

Singh Y, Humphreys E, Kukal SS, Singh B, Kaur A, Thaman S, Prashar A, Yadav S, Timsina J, Dhillon SS, Kaur N (2009a) Crop performance in permanent raised bed rice–wheat cropping system in Punjab. Indian Field Crops Res 110(1):1–20

Singh RP, Huerta-Espino J, Bhavani S, Singh D, Singh PK, Herrera-Foessel SA, Njau P, Wanyera R, Jin Y (2009b) Breeding for minor gene-based adult plant resistance to stem rust in wheat. In: McIntosh R (ed) Proceedings BGRI rust workshop, Obregon, Mexico, 17–20 March 2009

Singh RP, Hodson DP, Huerta-Espino J, Jin Y, Bhavani S, Njau P, Herrera-Foessel S, Singh PK, Singh S, Singh VG (2011) The emergence of the Ug99 fungus of the stem rust fungus is a threat to world wheat production. Annu Rev Phytopathol 49:465–448. https://doi.org/10.1146/annurev-phyto-072910-095423

Singh RP, Singh PK, Rutkoski J, Hodson DP, He X, Jørgensen LN, Hovmøller MS, Huerta-Espino J (2016) Disease impact on wheat yield potential and prospects of genetic control. Annu Rev Phytopathol 54:303–322

Snape JW, Chapman V, Moss J, Blanchard CE, Miller TE (1979) the crossibility of wheat varieties with *Hordeum bulbosum*. Heredity 42:291–298

Solomon A (2017) Performance evaluation of walking tractor drawn wheat planter. Ethiop Acad Res J Agric Sci Res 5:529–538

Spearling L, Loevinsohn ME (1993) The dynamics of adoption: distribution and morality of bean varieties among small farmers in Rwanda. Agric Syst 41:441–453

Stein N, Herren G, Keller B (2001) A new extraction method for high-throughput marker analysis in a largegenome species such as *Triticum aestivum*. Plant Breed 120:354–356

Sujan MHK, Islam F, Azad MJ, Rayhan SJ (2017) Financial profitability and resource use efficiency of *boro* rice cultivation in some selected area of Bangladesh. Afr J Agric Res 12:2404–2411

Tahir M, Ali A, Nadeem MA, Hussain A, Khalid F (2009) Effect of different sowing dates on growth and yield of wheat (*Triticum aestivum* L.) varieties in district Jhang, Pakistan. Pak J Life Soc Sci 7(1):66–69

Taiz L, Zeiger E (2002) Plant physiology, 3rd edn. Sinauer Associates, Sunderland

Timsina J, Connor DJ (2001) Productivity and management of rice-wheat cropping systems: issues and challenges. Field Crop Res 69:93–132

Timsina J, Wolf J, Guilpart N, van Bussel LGJ, Grassini P, van Wart J, Hossain A, Rashid H, Islam S, van Ittersum MK (2018) Can Bangladesh produce enough cereals to meet future demand? Agric Syst 163:36–44

UN (The United Nations) (2015) World population prospects, the 2015 revision. Department of Economics and Social Affairs, New York. http://esa.un.org/unpd/wpp/Download/Standard/Population/. Accessed 06 Apr 2016

United States Department of Agriculture (2018) FAS Home/Market and trade data/PSD online. USDA, Foreign Agricultural Service, Washington, DC. Available from URL: https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery. Accessed 28 Sept 2018

Velu G, Singh RP, Huerta-Espino J, Peña RJ, Arun B, Mahendru-Singh A, Mujahid MY, Sohu VS, Mavi GS, Crossa J, Alvarado G (2012) Performance of biofortified spring wheat genotypes in target environments for grain zinc and iron concentrations. Field Crop Res 137:261–267

Wheat Atlas (2016) Global distribution of wheat mega environments. International Maize and Wheat Improvement Center (CIMMYT), El Batan (Mexico). http://wheatatlas.org/megaenvironments. Accessed 1 Apr 2016

Witcombe JR (1999) Do farmer participatory methods apply more to high potential areas than to marginal ones? Outlook Agric 28:43–49

World Bank (2009) Bangladesh – country assessment strategy FY 2011–2014. Bangladesh Country Management Unit, South Asia Region, The World Bank Office, Dhaka

World Bank (2017a) Population estimates and projection. World Bank, Washington, DC. http://databank.worldbank.org/data/reports.aspx?source=Health%20Nutrition%20and%20Population%20Statistics:%20Population%20estimates%20and%20projections#. Accessed 14 July 2017

World Bank (2017b) World development indicators 2017: poverty headcount ratio at USD1.90 a day (2011 PPP) % of population. The World Bank, Washington, DC. http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators. Accessed 10 Jan 2017

World Bank (2018a) GDP per capita (current US$). World Bank, Washington, DC. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=BD. Accessed 06 Apr 2018

World Bank (2018b) World development indicators: renewable internal freshwater resources per capita (cubic meters). World Bank, Washington, DC. http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators. Accessed 24 July 2018

WRC (Wheat Research Center) Bangladesh (2018) WRC internal review report 2017–18. Presented in internal research review and programme planning workshop 2018, Wheat Research Centre, BARI, Presented on 15–17 July, 2018, Bangladesh Agricultural Research Institute (BARI), Joydebpur, Dhaka

Xie Q, Mayes S, Sparkes DL (2016) Optimizing tiller production and survival for grain yield improvement in a bread wheat× spelt mapping population. Ann Bot 117(1):51–66

Yagmur M, Kaydan D (2009) The effects of different sowing depth on grain yield and some grain yield components in wheat (*Triticum aestivum* L.) cultivars under dryland conditions. Afr J Biotechnol 8(2):96–201