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REVIEW

Mitigating the twin problems of malnutrition and wheat blast by one wheat variety, 'BARI Gom 33', in Bangladesh

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Abstract

For the first time in history outside of Latin America, deadly wheat blast caused by the fungus *Magnaporthe oryzae* pathotype *triticum* (MoT) emerged in the 2015–2016 wheat (*Triticum aestivum* L.) season of Bangladesh. Bangladesh, a country in South Asia, has a population of nearly 160 million, of which 24.3% are classified as poor. Consequently, malnutrition and micronutrient deficiency are highly prevalent, particularly among school going children and lactating women. Bangladesh Wheat and Maize Research Institute (BWMRI), with the technical support of the International Maize and Wheat Improvement Center (CIMMYT), Mexico, has developed and released a new wheat 'BARI Gom 33'. The new wheat is a zinc-enriched (Zn) biofortified wheat, resistant to the deadly wheat blast disease. 'BARI Gom 33' provides 5–8% more yield than the check varieties in Bangladesh. Rapid dissemination of it in Bangladesh, therefore, can not only combat wheat blast but also mitigate the problem of Zn deficiency and ensure income for resource-poor wheat farmers. Importantly, a large portion of the current wheat area in India and Pakistan is vulnerable to wheat blast, due to the similarities of the agro-climatic conditions of Bangladesh. As wheat blast is mainly a seed-borne disease, a rapid scaling out of the new wheat in Bangladesh can reduce the probability of MoT intrusion in India and Pakistan, and thereby generate positive externalities to the food security of more than 1 billion people in South Asia. This study explains the development process of 'BARI Gom 33'; the status of malnutrition in Bangladesh, and the possible economic gain from a rapid scaling out of 'BARI Gom 33' in Bangladesh. A few policies are recommended based on the discussions.

Keywords

biofortified wheat; zinc deficiency; wheat blast; Bangladesh; South Asia

Introduction

It is projected that the population of the world will be 9.1 billion in 2050 [1] from its 2018 level of 7.53 billion [2]. This rapid increase in population may worsen the current food security situation. At present, one in every nine people in the world (a total 815 million) are undernourished [3], and 2 billion people are suffering from hidden hunger due to micronutrient deficiency [4]. It is projected that to ensure food security of the burgeoning population by 2050; it is imperative to increase the net food supply by 70% [1]. As poor nutrition intake is responsible for 45% of deaths of children under 5 years of age every year [3], and 25% of children are suffering from stunted growth [3], it is essential to ensure the supply of micronutrient-enriched food to defeat the problem of hidden hunger across the globe.

While it is imperative to supply more food and more micronutrient-enriched food, the recent spread of lethal crop diseases has been continuously creating severe threats to food security. For example, the emergence of wheat stripe rust (*Puccinia striiformis* f. sp. *tritici*) in Australia [5,6], the re-emergence of wheat stem (or black) rust in Africa and the Arabian Peninsula [7], maize lethal necrosis (MLN) in Kenya [8] and the spread of fall army worm in Africa [9] and its recent spread in India [10], have all threatened global food security. The emergence of the deadly wheat blast in Bangladesh in the 2015–2016 wheat season is the most recent addition to such threats [11–14].

In February 2016, wheat blast emerged in Bangladesh, for the first time in history outside of Latin America. This deadly wheat disease can destroy wheat yield by up to 100% in extreme cases [15]. Even the application of fungicides cannot completely control the disease [15]. In the 2015–2016 wheat season in Bangladesh, wheat blast affected nearly 15,000 ha, or 3.5% of the total 436,817 ha of wheat cropland, and reduced wheat yield by 5–51% in the affected fields [11]. The disease emerged again in the 2016–2017 and 2017–2018 wheat seasons [13,14].

The emergence of the wheat blast in Bangladesh has generated severe threats to the food security of more than a billion people in South Asia. A recent study [13] warned that out of a total of 40.85 million ha of wheat cropland in Bangladesh, India, and Pakistan, nearly 7 million ha (17.1%) is vulnerable to wheat blast. Currently, wheat in India and Pakistan is the major staple food [16], and the choice of wheat as a food item has been gaining popularity in Bangladesh, which is the second major staple after rice [17]. Regarding international trade, India is a net exporter of wheat, Pakistan is almost self-sufficient, and Bangladesh is a net importer of wheat [18]. As it is projected that the population of South Asia will increase to 2.29 billion by 2050 from 1.74 billion in 2015 [2], South Asia needs to increase wheat production by 2.25% every year to meet the growing demand of the burgeoning population [16]. Currently, 14.7% of the total population in South Asia are already extremely poor [2]. A possible spread of *Magnaporthe oryzae* pathotype *triticum (*MoT) from Bangladesh to India and Pakistan and a reduction of wheat production due to the spread of wheat blast would generate severe negative impacts on the food security and poverty situation in the entire region. Conversely, a reduction of the problem of wheat blast in Bangladesh can generate significant positive outcomes in South Asia. The successful mitigation of the wheat blast problem in Bangladesh could reduce the wheat blast threat to India and Pakistan, two of the major wheat producers and consumers in South Asia.

With the aim to find a long-term sustainable solution to combat wheat blast, Bangladesh Wheat and Maize Research Institute (BWMRI), in collaboration with the International Maize and Wheat Improvement Center (CIMMYT), Mexico, has developed and tested 'BARI Gom 33', a new wheat variety. After multilocation national level trials, and screening against wheat blast in 2016 and 2017 under field and laboratory conditions in Bangladesh (Jashore), Bolivia (Instituto Nacional de Innovacion Agropecuaria y Forestal; INIAF), and in the USA [United States Department of Agriculture-USDA-ARS (Agricultural Research Service) Laboratory, Maryland], the variety was confirmed resistant to wheat blast. Moreover, the new wheat is moderately resistant against *Helminthosporium* leaf blight and leaf rust diseases, common wheat diseases in Bangladesh [19]. The new wheat also provides 5–8% more yield than any check varieties under normal condition. Finally, the new wheat is also zinc enriched (40–45 ppm zinc) in the grains with a zinc advantage of 7–8 ppm over local varieties [19]. On October 11, 2017, in the 93rd National Seed Board Meeting, the Bangladesh National Seed Board approved 'BARI Gom 33' as a new variety to release. 'BARI Gom 33' carries 2NS segment for blast resistance, which is evident from the marker analysis.

Importantly, the new wheat 'BARI Gom 33' is a zinc-enriched (Zn) biofortified wheat with 32.09 and 50–55 ppm zinc without and with soil application of $ZnSO_4$. The Zn trait of the new wheat can have a significant positive impact on the nutritional status of Bangladeshi consumers. Of nearly 160 million people in Bangladesh, 24.3% are living below the national poverty line. In addition to the problem of visible hunger, hidden hunger in the form of malnutrition and micronutrient deficiency are highly prevalent in Bangladesh. For example, currently 36% of children under 5 years of age in Bangladesh are stunted, and 31% of married women aged 15–19 are undernourished [20]. Alarmingly, mostly due to iron deficiency, 92% of infants aged 6–11 months in Bangladesh suffer from anemia [21]. It has been estimated that due to massive undernutrition, Bangladesh is losing labor productivity worth US$ 1 billion yearly [22]. The damage in the human body due to micronutrient deficiency in childhood is irreversible. The rapid upscaling of the zinc-enriched 'BARI Gom 33' could significantly contribute to combatting massive undernourishment in the country and to developing quality human resources, which is the fundamental ingredient of the economic development of a nation. Rapid dissemination and adoption of this new wheat in Bangladesh, therefore, can combat two pressing problems: malnutrition and wheat blast.

This study is organized as follows. Section "Micronutrient deficiency scenario: global and Bangladesh" presents the Zn deficiency scenario at the global and Bangladesh level. Section "The major syndromes of Zn deficiency in humans" includes the major symptoms of Zn deficiency in the human body. Section "The breeding procedure of Zn enriched and wheat blast resistant variety 'BARI Gom 33'" explains the breeding process of 'BARI Gom 33', and section "Potential economic benefits of biofortified and blast-resistant wheat variety 'BARI Gom 33'" presents the potential economic benefits and losses of the dissemination of the new wheat. Finally, last section includes conclusions and policy implications.

Micronutrient deficiency scenario: global and Bangladesh

The advent of the "green revolution" in the 1960s, mainly in the form of the expansion of high-yielding, semi-dwarf, irrigation- and fertilizer-responsive wheat and rice across the globe, remarkably improved food availability, and thereby the food security status of the world. For example in 1961, the total cereal production in the world was 876.9 million metric tons (MMT), with 128.9 kg availability yearly per capita. In 1970, total cereal production reached 1.2 billion MMT, which was 36% more than the 1961 level, reaching the availability level at 138.5 kg yearly per capita [18]. In 2017, total cereal production in the world reached nearly 3 billion MMT with yearly per capita availability of more than 147 kg. Consequently, despite the total population of the world increasing by 148% from 3.03 billion in 1960 to 7.53 billion in 2017, the absolute number of the undernourished population in the world has declined from 18.6% in 1961 to 10.6% in 2015.

Despite success in combating visible hunger, hidden hunger in the form of micronutrient deficiency is still highly prevalent, particularly in the developing countries of South Asia and Sub-Saharan Africa. Currently, more than 2 billion individuals in the world are suffering from micronutrient deficiency, such as zinc (Zn) and iron (Fe) [23,24]. Worldwide, about 20% of deaths of children under 5 years of age are solely attributable to vitamin A, Zn, Fe, or iodine deficiency [25]. Such micronutrient deficiency emerges when the intake of minerals and vitamins is too low to sustain health and development [26]. To fight hidden hunger in developing countries across South Asia and Africa, where cereals and tubers, such as rice, wheat, maize, and sweet potatoes, are the major food items, researchers and policymakers are increasingly opting for biofortified cereals. Biofortification is the idea of breeding crops to enhance their nutritional value, such as enhancing vitamin A, iron, and zinc in the crops, which can be done through different agronomic practices, conventional plant breeding, or applying modern biotechnology [27]. Under this initiative, a total of 13 crops across the globe were biofortified and released in 20 countries [28]. The biofortified crops are banana, bean, cassava, cowpea, Irish potato, lentil, maize, pearl millet, pumpkin, rice, sorghum, sweet potato, and wheat [28]. By 2018, these crops had been released in 19 countries: Bangladesh, Brazil, Burkina Faso, China, DR Congo, Ethiopia, India, Indonesia, Ivory Coast, Kenya, Mozambique, Nepal, Nigeria, Pakistan, Philippines, Rwanda, Syria, Uganda, and Zambia [28].

Bangladesh is one of the major beneficiaries of the green revolution. In 1970, total cereal production of the country was only 16.9 MMT, and in the entire 90s, the country often faced the problem of food shortages. By 1990, the total cereal production of the country reached nearly 28 MMT, and by 2017 it was 53.3 MMT. Bangladesh is now almost self-sufficient in rice production and has not faced any severe food shortage problems since the 1970s. The number of undernourished people who are in absolute hunger in Bangladesh has drastically reduced due to the availability of grain. In 2000, out of a population of 132 million, 34.3% were extremely poor, whereas in 2016, of 163 million, 12.9% were extremely poor. However, even today, because of micronutrient deficiency, 41% of the children under 5 years of age are chronically undernourished and therefore stunted; one-third of children from 6 months to under 5 years of age are anemic; and 24% of the women in Bangladesh are underweight [24]. Due to productivity loss, the estimated overall costs of this is US$ 1 billion per year [24]. As rice and wheat are the major food items in Bangladesh, the government has been trying to enhance the adoption and dissemination of biofortified rice and wheat. The first biofortified Zn enriched rice 'BRRI Dhan 72' was released in Bangladesh in 2016, and in 2017, the second biofortified crop, the Zn enriched wheat 'BARI GOM 33' was released.

Global scenario on the Zn deficiency

The essential micronutrients for the human body are iron (Fe), zinc (Zn), iodine (I), selenium (Se), calcium (Ca), fluorine (F), and vitamins A, B1, B2, B3, B6, B12, and C [29]. By using data on diet and bioavailability, studies estimated that at least one-third of the population in the world has Zn deficiency, particularly children [30,31]. Among them, every year approximately 450,000 children under 5 years of age face death due to Zn deficiency [32]. The World Health Organization (WHO) reported a 31% Zn deficiency across the globe [33]. A study [34] found that underdeveloped nations suffering from Zn deficiency face a high rate of mortality, due to childhood diarrhea and pneumonia [35]. Zn is particularly prominent in the male prostate gland and semen.

The National Institutes of Health, USA [36] recommended daily intakes for people [37] (Tab. 1), according to age, sex, and growth stage of males and females. Zn deficiency is categorized as the fifth leading cause of various diseases worldwide. It was estimated that about 800,000 deaths among children below 5 years of age occur annually due to Zn deficiency, which includes 176,000 deaths from diarrhea, 406,000 deaths from pneumonia, and 207,000 deaths from malaria, mainly in South East Asia, the Eastern Mediterranean, and Africa [27,38] (Fig. 1).

Tab. 1 Recommended dietary intake of Zn for the human.

Age	Male (mg)	Female (mg)	Pregnancy (mg)	Lactation (mg)
0–6 months	2	2	-	-
7–12 months	3	3	-	-
1–3 years	3	3	-	-
4–8 years	5	5	-	-
9–13 years	8	8	-	-
14–18 years	11	9	12	13
19+ years	11	8	11	12

Source: [37].

Zn deficiency scenario in South Asia including Bangladesh

In South Asia, including Bangladesh, more than 26% of the population have inadequate Zn intake. As a result, people are suffering from various diseases, particularly due to Zn deficiency in early childhood [39,40]. Zn is an "essential" trace element for everybody to remain alive. Similarly, plants and animal also need a specific amount of Zn in their various growth stages. Women and children are the most vulnerable to micronutrient deficiencies. The scenario in Bangladesh was also exposed in the *National micronutrients status survey 2011–12* [41] (Fig. 2).

Generally, people in Bangladesh depend on staple cereals (mainly rice and wheat) for the majority of their dietary energy, and essential micronutrients such as Fe, Zn, I, Se, Ca, F, and vitamins. Among the micronutrients, Zn plays the most significant role in the human body. A survey conducted by the International Center for Diarrhoeal

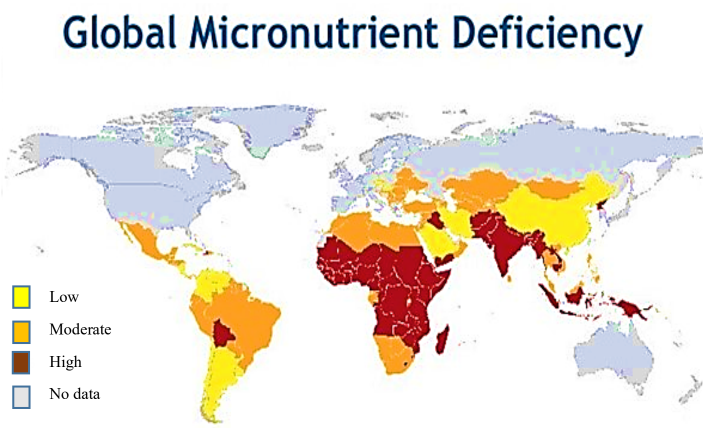


Fig. 1 Most common micronutrients deficiency status in the world. Data source: WHO children under 5 years of age prevalence data. Severity was calculated using a weighting system based on levels of publishing health significance cut-offs (low, moderate, and high). Sources: [27,38].

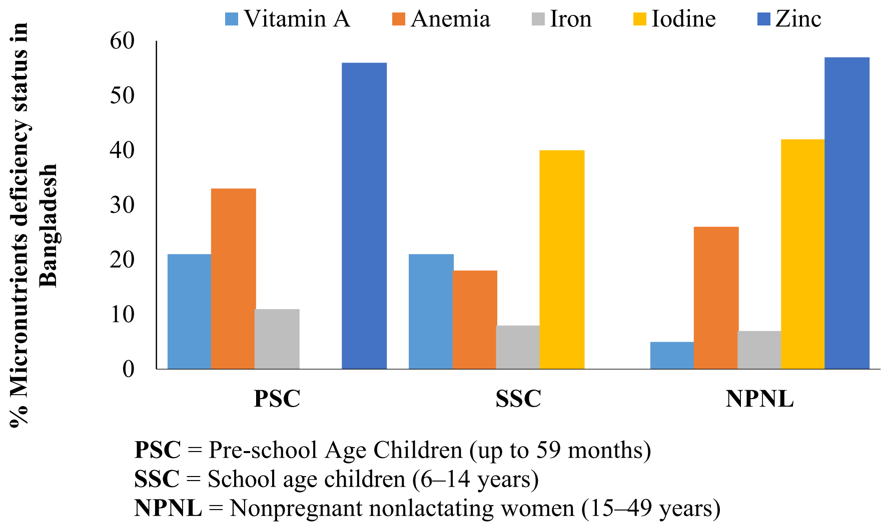


Fig. 2 Micronutrient deficiency in Bangladesh (percent of the surveyed population). Source: [41].

Disease Research, Bangladesh (Icddr, b) [41] reported that preschool age children (up to 59 months) and nonpregnant and nonlactating women (15–49 years) face a 50% Zn deficiency in Bangladesh.

Dietary intake with low Zn concentration and a lack of a diversified diet are the major contributors to Zn deficiency [42,43]. In developing countries (including Bangladesh), diets are based on cereals' grains, and cereals are poor in Zn. Amelioration of cereals' grains with Zn is, therefore, a vital worldwide challenge [44]. Genetic biofortification (plant breeding) and agronomic biofortification (application of fertilizer containing Zn) are two of the most significant agricultural approaches to increasing Zn concentration in cereals' grain [45–47].

Additionally, through the breeding program, newly developed Zn enriched genotypes could accumulate a sufficient amount of Zn if Zn is available in soils. On the other hand, grain of wheat is generally intaken after milling. However, during the milling process, the bran and embryo parts of seeds, which are enriched in Zn, are removed; the part (endosperm) which are used in the human diet has a low concentration of Zn [48,49]. Therefore, it is important to enrich the Zn concentration in the endosperm of the cereal grains through biofortification. Scientists around the globe are trying to improve Zn and Fe concentrations in endosperm by using molecular genetic approaches [50,51].

The major syndromes of Zn deficiency in humans

Many people in South-East Asia, the Eastern Mediterranean and Africa are zinc deficient [23,39]. Among them, women and children are the most vulnerable to micronutrient deficiencies and are unaware of their condition. The seven most common Zn deficiency indications are described below.

Frail immunity in the human body

Zn is needed to conserve the immune function of the human body [52]. It is the active element for the growth of T cells, as a protective function of cell membranes, and also helps to differentiate the white blood cells which are essential to ward off disease. Zn prevents apoptosis disease (involuntary cell-death) through killing dangerous bacteria, viruses, and cancer cells. It also plays a key role in a slew of hormone receptors and a structural component of proteins to preserve health and steadiness of mood.

Diarrhea disease

Persistent diarrhea is a major public health concern, which occurs mostly due to weakened immunity that is caused by a Zn deficiency. Two million children in developing countries every year have diarrhea, due to colds and other bacterial infections [53]. Supplementation of Zn for babies older than 6 months has been found effective to control diarrhea disease [54].

Limited neuropsychologic function

Zn is undeniably essential for growth and neuropsychological function. Low Zn levels are linked with several disorders in infants that persevere into adulthood [55,56]. Chinese findings published in the *American Journal of Clinical Nutrition* revealed that a Zn supplement in daily food provides just 50% of the recommended daily allowance [56]. The investigation also found that Zn is best absorbed with a proper balance of other nutrients from food. Consequently, it is imperative that individuals be in contact with a physician to ascertain Zn deficiency status, for proper human growth and neuropsychological function.

Allergies

Chronic stress causes adrenal fatigue, and leads to Ca, Mg, and Zn deficiencies; this raises histamine levels in the human body [57]. Zn is a key micronutrient that maintains histamine levels. Zn deficiency sanctions more histamine, which surrounds tissue with fluids; as a result, surplus histamine promotes allergy symptoms such as a running nose, sneezing, hives, etc.

Thinning hair

Battling adrenal fatigue is a common health concern, and Zn deficiency is associated with hypothyroidism. An ignored aspect of Zn deficiency is thinning hair and alopecia [58]. Consequently, hypothyroidism causes hair loss due to the limitation of the thyroxine hormone, and since Zn supplementation could improve thyroxine in the human body, this would also result in decreased hair loss [58].

Intestinal permeability (leaky gut)

First observed 70 years ago, leaky gut (intestinal permeability) can cause a slew of autoimmune diseases, skin disorders, allergies, nutrient malabsorption, and thyroid problems [54]. Zn supplementation has been found to clinically help resolve the intestinal permeability alterations of leaky gut in Crohn's patients [59].

Skin rashes or spots

Leaky gut causes various skin diseases such as skin rashes. These types of symptoms are absent under sufficient Zn supplementation [55]. It is thus confirmed that Zn is an essential micronutrient for the human body. Its deficiency is associated with seven common diseases such as frail immunity, diarrhea, poor neuropsychological function, allergies, thinning hair, leaky gut, and acne or rashes. The daily recommended amount of Zn could be achieved through biofortified foods or medicine.

The breeding procedure of Zn enriched and wheat blast resistant variety 'BARI Gom 33'

Researchers in Bangladesh are working with the HarvestPlus program in collaboration with different national and international organizations and have already developed four biofortified rice varieties by using a breeding approach, although Zn concentration ranged from 19.60 to 24.60 ppm in the rice. Similarly, BWMRI [previous name: Wheat Research Centre of Bangladesh Agricultural Research Institute (BARI)] have been working closely with CIMMYT to develop and deploy biofortified wheat varieties since 2013. As an output of the collaborative research, Bangladesh released the biofortified wheat variety 'BARI Gom 33' (before releasing named: 'BAW 1260') in 2017 (Fig. 3) [60]. Under multilocation trials (farmers' fields) the average yield was recorded at 3.97 to 4.5 t ha^{-1}, with a high yield potential of 6.04 t ha^{-1} (at the research trial). It possesses 2NS translocation, which indicates a good level of tolerance against wheat blast and is enriched with 50–55 ppm Zn.

Fig. 3 'BARI Gom 33' at a grain-filling stage in the research field of Bangladesh Wheat and Maize Research Institute (BWMRI), Dinajpur-Bangladesh. Adapted from [60].

Material selection

The variety 'BARI Gom 33' was selected from the CIMMYT international nursery through the conventional breeding procedure. CIMMYT developed the cultivars through a simple cross between two kinds of wheat such as 'Kachu' and 'Solala'. 'Kachu' is a 'Kauz'-derived high-yielding wheat variety carrying 2NS segment for partial blast resistance. 'Solala' derived from a CIMMYT's prebreeding cross involving the durum wheat derivative of *T. polonicum* with a long spike (CMH74A.630/SUPER X//CIANO T 79/3/IRENA) [60]. The simple cross derived F_1s were planted in El Batan, Mexico during 2010, and the F_2 populations of about 2,000 plants were grown in Cd. Obregon, Mexico. The best plants with good leaf rust resistance were selected and bulk harvested. The F_3 and F_4 bulks of about 400–800 plants were grown and plants resistant to yellow rust and leaf rust in Toluca and Cd. Obregon, respectively, was bulked. F_5 bulks of about 800 plants were grown in Toluca during the 2012 crop season, with yellow rust and *Septoria tritici* blotch resistant plants harvested, and individual head-rows made. Visual selection of plump and bold grains from individual heads were advanced to Cd. Obregon as head-rows. The head-rows were evaluated in small plots with repeated checks for agronomic characteristics and resistance to leaf and stem rusts at Cd. Obregon. Best performing F_6 head-rows exhibiting resistant to rusts, superior agronomic performance, and bold and plump grain types were analyzed for Zn and Fe concentrations, initially with X-ray fluorescence (XRF) spectrometer and then with inductively coupled plasma optical emission spectrometry (ICP OES) analysis at the Waite Analytical Services Laboratory, Australia. Grain protein percentage and grain hardness were measured using the near infra-red spectroscopy (NIRS) assay at the CIMMYT Wheat Quality Laboratory [60].

The F_6 fixed lines were advanced to first yield trials grown with alpha-lattice-Latinized design with three reps, two checks, and 28 entries in each trial at Cd. Obregon, during the 2013–2014 crop season. The chelated form of Zn fertilizer was applied to optimize and homogenize available soil Zn and to reduce soil Zn heterogeneity at Cd. Obregon experimental station. Agronomic data on days-to-heading, maturity, plant height, and agronomic attributes were recorded for all entries. Yield potential of 'Kachu' / 'Solala' (sisters) ranged from 5.9 to 7.7 t ha^{-1} with an average yield of 6.6 t ha^{-1} in Mexico. Considering grain Zn and grain yield, 'Kachu' / 'Solala' was phenotyped in five artificially managed environments in Cd. Obregon [60]. On average, about 5% yield superiority was found across five environments and in late-sown heat environment, where continuous heat stress occurs during the crop growing season and higher terminal heat stress towards the end of the crop season. This environment replicates most of the mega-environments (ME) of the five types of environments in South Asia including Bangladesh, the Eastern Gangetic Plains (EGP) of India and Nepal. Based on the performance from Mexico, 'Kachu' / 'Solala' was included in the fourth harvest plus yield trial (HPYT) trial, and was distributed to national partners in South Asia including Bangladesh, and evaluated during the 2013–2014 crop season. This entry showed good performance across locations for grain yield and 6–8 ppm Zn increment over local checks and bold grain size (50 g TGW).

Multienvironmental adaptive trials before releasing as a variety

The adoption of new agricultural technology, including improved seeds, is seldom instantaneous [61]. For one, the new technology needs to be available to farmers to be potentially adopted. A new variety needs to have its seed bulked up, often initiated only after its formal release. Furthermore, technology adoption is a complex process influenced by a large number of factors [62,63], including risks and uncertainties about proper application, suitability with the environment and farmers' expectations [59]. As a result, the adoption process can be slow [64] and may fail in the absence of strong public support and extension services.

Being selected from the fourth HPYT in the 2013–2014 season, the entry was evaluated from the Zn-enriched wheat yield trial in Gazipur (ME 5) and Dinajpur (ME 1) station of BARI. This line had an exceptional phenotype, good grain yield and better adaptation with high grain Zn content. Hence the entry advanced to the preliminary yield trial (PYT) in the 2014–2015 season with the accession number BAW 1260 (presently BARI Gom 33). Mean yield of 'BAW 1260' over a local check ('BARI Gom 24') was about 8% and 5% higher in timely and late planting conditions, respectively. Thus the entry was promoted to advanced yield trial (AYT) in the 2015–2016 season to evaluate in five different BARI stations across the country where mean yield was again higher than the check at 6% and 15%, respectively. In 12 different sites of the adaptive trial, 'BAW 1260' was found to have the highest yield (6.04 t ha^{-1}) in Dinajpur with a trial

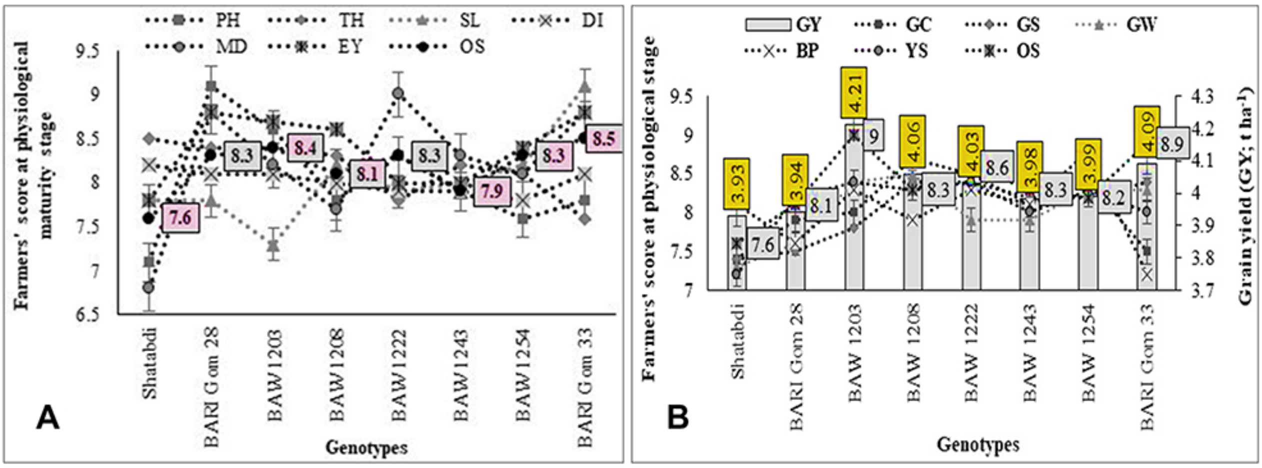


Fig. 4 Farmers' preference scores for different traits of seven selected wheat genotypes including 'BARI Gom 33' applying a participatory varietal selection method during the 2016–2017 season. PH – plant height; TH – tillering habit; SL – spike length; DI – disease incidence; MD – maturity days; EY – expected yield; OS – overall score; GC – grain color; GS – grain size; GW – grain weight; BP – black point; YS – score on yield basis; GY – grain yield. Data source: [60].

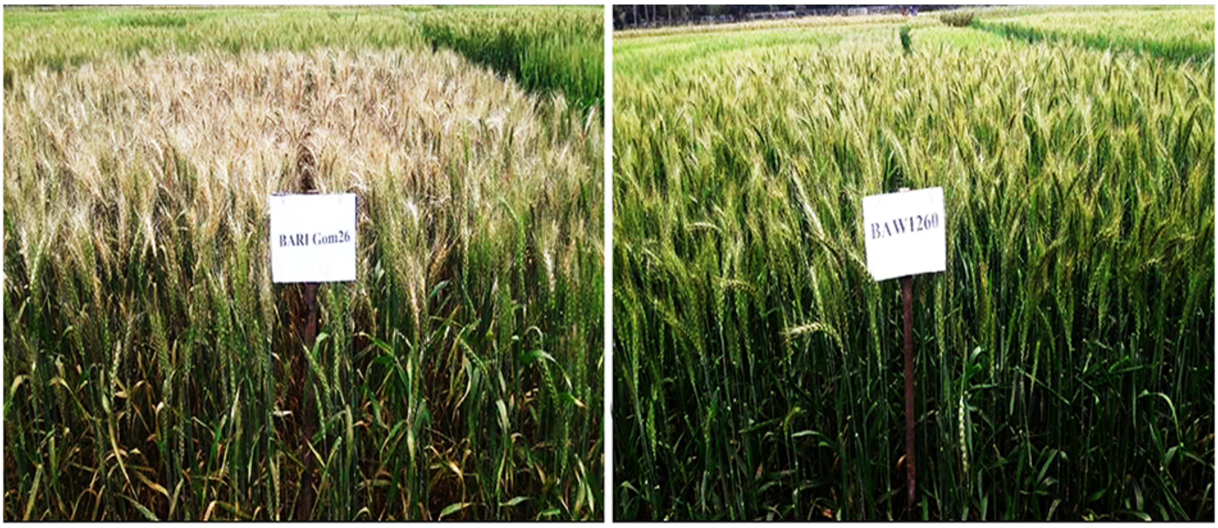
average yield of 3.97 t ha^{-1}. In the participatory variety selection (PVS) trial, farmers' overall score at physiological maturity stage was the highest for 'BAW 1260' (Fig. 4). Farmers chose this genotypes for its longer spike and higher expected yield, although it ranked second after harvest score. However, 'BARI Gom 33' ('BAW 1260') was the highest preferred genotype over locations in Bangladesh [60].

Wheat blast: a new threat to food security

Wheat blast was mainly native to Latin American countries [11,12,65–67]. However in 2016, the disease emerged in Bangladesh, and approximately 15,000 ha land was affected (3.5% of the total 0.43 million ha of wheat area), with yield loss ranging between 5% to 51% [11,65]. The disease reappeared in the following two seasons (2017–2018 and 2018–2019 wheat seasons). However, the disease severity was comparatively low (yield loss was about 5–10% and 1–5%, respectively) (Tab. 2, Fig. 5) [11,12,60,65,67,68]. Since wheat blast was reported for the first time in Bangladesh in 2016 [11,12,65], there is a possibility the disease will spread in South Asian countries particularly India, Pakistan, Nepal, and China [69,70]. As a result of this first incidence of wheat blast in South Asia, the international plant pathologies community and the governments of these countries

Tab. 2 Comparative status of wheat blast incidence in Bangladesh in the 2015–2016, 2016–2017, and 2017–2018 wheat seasons. Adapted from [65].

Events	2016	2017	2018
Infection time	Mid-February	Mid-January	Early February
Weather situation	Rain at flowering time (35 mm in February) 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, Jashore, Magura, Kushtia, Barishal, Bhola	Previous districts + some additional districts: Faridpur, Rajshahi, Pabna	Meherpur, Jhenaidah, Chuadanga, Jashore, Kushtia, Bhola, Faridpur, Rajshahi, Rajbari, Natore, Tangail, Jamalpur, Cumilla



Wheat blast susceptible variety 'BARI Gom 26' in the field condition of Jashore- Bangladesh

Wheat blast resistant variety 'BARI Gom 33' in the field condition of Jashore- Bangladesh

Fig. 5 Variety 'BARI Gom 33' showing resistance against wheat blast in the field conditions of Jashore – Bangladesh. Adapted from [60].

began to develop short, medium, and long-term strategies to limit the spread of the disease as well as turn their attention to sustaining wheat production in this region to face the lethal disease[14,68,71].

Scientists and policymakers in the region took several initiatives in collaboration with CIMMYT, ACIAR, and the USA for the development of a wheat blast resistant wheat variety. A comprehensive breeding program was undertaken to identify sources of resistance to wheat blast and their deployment adapted wheat genotypes in collaboration with CIMMYT/ACIAR. A precision phenotyping platform (PPP) has been established at Jashore for large-scale screening against wheat blast with support from CIMMYT and ACIAR. During the 2017–2018 wheat season, about 5,000 germplasm were received from CIMMYT and had been screened against wheat blast, and some resistant genotypes have been identified. In the meantime, the genotype 'BARI Gom 33' was found to have a good level of tolerance against wheat blast and was released as a variety in 2017.

Field test of wheat blast resistance wheat variety 'BARI Gom 33'

The outbreak of wheat blast occurred in the 2015–2016 season in Bangladesh when 'BARI Gom 33' was in AYT at Jashore, and interestingly this entry had no blast infection, which attracted the breeders for the potential of a blast-resistant wheat variety. The Jashore location was found favorable for wheat blast according to 3 years of data of the wheat blast trials. Ten elite wheat varieties/lines were tested in the location, and all varieties/lines showed varying levels of resistance and susceptibility to the disease. Among them, seven lines were graded as resistant, six moderately resistant, seven moderately susceptible, and the remaining five as highly susceptible. Borlaug 100, and 'BARI Gom 33' showed a resistant reaction, while 'BARI Gom 26' displayed a highly susceptible reaction. The resistant variety 'BARI Gom 33' was found with 1.8% disease severity, while the most susceptible variety 'BARI Gom 26' observed about 91.7% (Fig. 6) [65].

This entry was further evaluated for the wheat blast in "foreign disease-weed science research unit" of USDA-ARS, Frederick, USA, Instituto Nacional de Innovación Agropecuaria y Forestal (INIAF), Bolivia and RARS, Jashore, Bangladesh. Disease severity was estimated using standard 0–100 scale and the modified Cobb scale. The greenhouse screening with the inoculated condition in the USA resulted in the wheat blast score 11.1%, whereas it was found at 4.4% in Bolivia in field conditions, but no wheat blast infection was found in Jashore, Bangladesh.

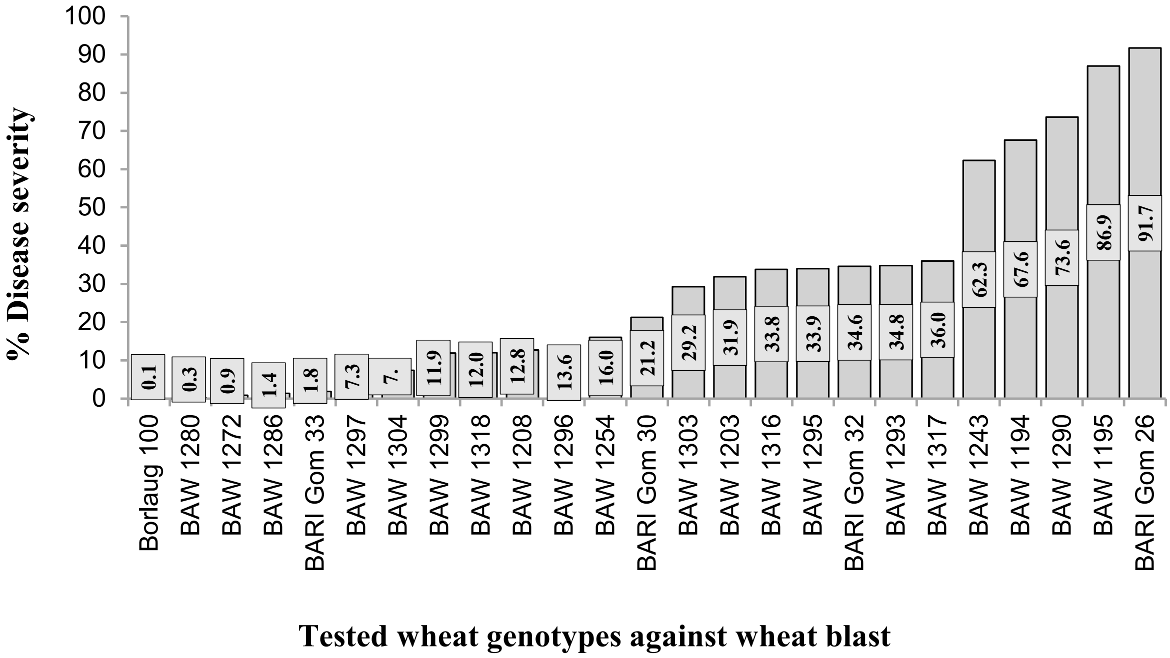


Fig. 6 Elite germplasm screening against wheat blast under the artificially inoculated condition. Adapted from [65].

Grain quality

End-use quality tests were conducted at the CIMMYT wheat cereal chemistry laboratory. Interestingly, this entry showed strong and balanced gluten, which is recommended for South Asian flatbread ("chapatti"). Grain hardness was classified as hard to semihard with protein contents of 11.8% to 12.5% in grain and 10.3% to 11.8% in flour. The dough development time was above 2.0 min, and the mixographic type was more than 3.0 in a scale of 1 to 5, indicating good dough mixing properties and suitability for making flatbread (chapatti) as well as yeast-leavened bread.

Potential economic benefits of biofortified and blast-resistant wheat variety 'BARI Gom 33'

As 'BARI Gom 33' is a blast resistant, Zn enriched wheat that can provide 5–8% more yield than the checks, rapid deployment of this wheat can solve the pressing twin problems of Bangladesh: wheat blast and Zn deficiency [72]. To accrue the benefits of 'BARI Gom 33', the new wheat should be disseminated as soon as possible, at least primarily in the currently wheat blast affected districts of Bangladesh. A speedy seed multiplication and dissemination process needs external supports. This is because, in the normal seed multiplication process, the new wheat may reach the hands of farmers in 4–5 years, given that agricultural technology adoption is a complex activity, and a large number of factors can affect the adoption process [73–75]. This is because new agricultural technologies are often correlated with risks and uncertainties about proper application and suitability with the environment, and farmers' expectations [64]. As a result, the adoption process can be slow [58], and the entire adoption process may fail in the absence of public supports and extension services. Strong external support, however, can speed up the seed multiplication and dissemination process.

In Fig. 7, possible adoption scenarios, the corresponding gains, and the counterfactual dead-weight losses are presented linking to the adoption of 'BARI Gom 33', assuming the new wheat adoption will begin in the 2018–2019 wheat season. Under the assumption of a 30% maximum adoption rate in all cases, we have developed three distinct adoption pathways considering a logistic adoption function. In Case 1, the adoption

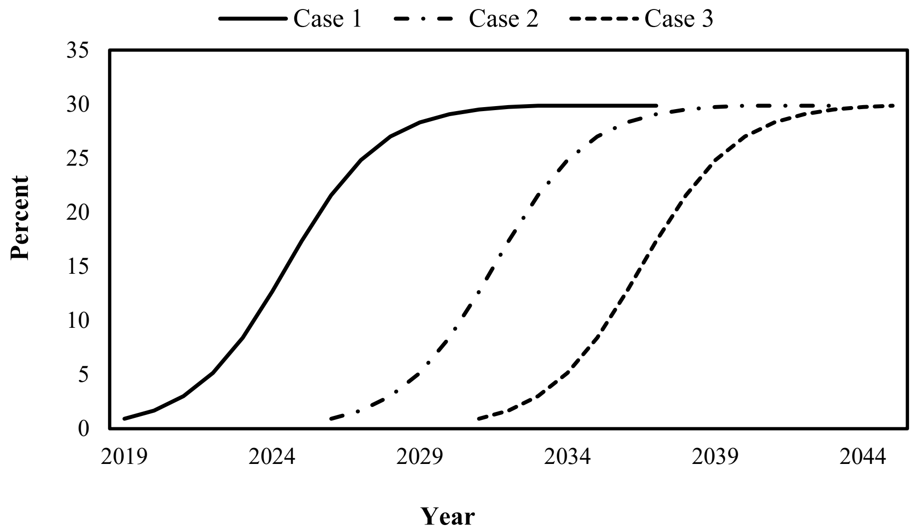


Fig. 7 Potential economic benefits from different adoption scenarios of 'BARI Gom 33'. Source: authors' estimation.

will start in the year 2019, and the maximum adoption rate will be achieved by 2033. In such a case, the total economic gain will be equivalent to area *a*+*b*+*c* (Case 1; Fig. 7). Conversely, area *a*+*b*+*c* will be the total dead-weight loss under the assumption of the zero adoption. In Case 2, the adoption will start in the year 2026, and the maximum adoption rate will be achieved by 2040. In such a case, the total economic gain will be equivalent to area *b*+*c* (Case 2; Fig. 7). In Case 2, the dead-weight loss will be equivalent to the area *a* (Case 2; Fig. 7). In Case 3, the adoption will start in the year 2031, and the maximum adoption rate will be achieved by 2045. In such case, the total economic gain will be equivalent to area *c* (Case 3; Fig. 7), and the dead-weight loss will be equivalent to area *a*+*b* (Case 3; Fig. 7).

Conclusions and policy implications

The emergence of the wheat blast in Bangladesh has generated severe threats to the food security of millions in South Asia. As wheat is the principal staple food of Pakistan, and the second most important staple food in India, a possible spread of the wheat blast from Bangladesh to India and Pakistan and a reduction of wheat production due to wheat blast would generate severe negative impacts on the food security and poverty situation in the region. Conversely, successful eradication of the wheat blast disease in Bangladesh can generate significant positive externalities in South Asia.

With an aim to find a long-term sustainable solution to combat the wheat blast and Zn deficiency in Bangladesh, the BWMRI, in collaboration with CIMMYT, developed and tested 'BARI Gom 33', a new wheat variety. After multilocation national level trials and screening against wheat blast in 2016 and 2017 under field and laboratory conditions, it is confirmed that the new wheat is the first blast resistant wheat in the world. Moreover, the new wheat provides 5–8% yield gain, and it is Zn enriched in the grains with zinc advantage of 7–8 ppm over local varieties. The dissemination of 'BARI Gom 33' will significantly contribute to combat the existing massive undernourishment of Bangladeshi households and consequently reduce the loss in labor productivity worth of US$ 1 billion, which stems from the massive undernourishment.

As under the existing dissemination process, it will take 4–5 years for the new wheat to reach the hands of farmers, and as a delay in deploying the new seeds can generate net loss, this study strongly urges external technical and financial support to speed up the dissemination process of 'BARI Gom 33' in Bangladesh.

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Zmniejszenie podwójnego problemu – niedożywienia oraz choroby grzybowej pszenicy poprzez zastosowanie odmiany pszenicy 'BARI Gom 33' w Bangladeszu

Streszczenie

W sezonie wegetacyjnym 2015–2016, po raz pierwszy w kraju spoza obszaru Ameryki Łacińskiej, w Bangladeszu, stwierdzono pojawienie się bardzo poważnej choroby pszenicy (*Triticum aestivum* L.) wywołanej przez pasożyta grzybowego *Magnaporthe oryzae* patotyp *triticum* (MoT). Liczba ludności w Bangladeszu, kraju leżącym we wschodniej Azji, wynosi około 160 milionów, z czego 24,3% jest uważana za dotkniętą ubóstwem. Dlatego niedożywienie i deficyty mikropierwiastków w diecie są szeroko rozpowszechnione, zwłaszcza wśród dzieci w wieku szkolnym i kobiet karmiących. Bangladeski Instytut Badawczy Pszenicy i Kukurydzy (Bangladesh Wheat and Maize Research Institute, BWMRI), przy technicznym wsparciu Międzynarodowego Centrum Ulepszania Kukurydzy i Pszenicy (International Maize and Wheat Improvement Center, CIMMYT) w Meksyku, wyhodował i udostępnił nową odmianę pszenicy 'BARI Gom 33'. Ta nowa odmiana jest wzbogacona w cynk (Zn) (na drodze biofortyfikacji) i jednocześnie odporna na zarazę grzybową. Plonowanie 'BARI Gom 33' jest o 5–8% wyższe w porównaniu z innymi odmianami pszenicy uprawianymi w Bangladeszu. W związku z tym, szybkie rozpowszechnienie tej odmiany do upraw mogłoby nie tylko ograniczyć zarazę pszenicy, ale również pomóc zniwelować problem deficytu cynku, zapewniając jednocześnie dochód ubogim rolnikom. Duża część upraw pszenicy w Indiach, Pakistanie i Bangladeszu jest podatna na tę chorobę grzybową ze względu na podobieństwo warunków agro-klimatycznych w tych krajach. Ponieważ choroba ta przenosi się głównie poprzez nasiona, szybkie wprowadzenie do upraw nowej odmiany pszenicy w Bangladeszu mogłoby zredukować prawdopodobieństwo przenikania MoT do Indii i Pakistanu, generując pozytywne skutki zewnętrzne w zakresie bezpieczeństwa żywności dla ponad miliarda ludności w Południowej Azji. W niniejszej pracy opisano proces hodowli odmiany 'BARI Gom 33', stan niedożywienia w Bangladeszu oraz potencjalne zyski ekonomiczne na skutek szybkiego rozpowszechnienia 'BARI Gom 33' w tym kraju. Wskazano również rożne scenariusze związane z wprowadzeniem 'BARI Gom 33' do uprawy.