Review Article

RICE AS THE LIFELINE OF BANGLADESH: CULTURAL HERITAGE AND PRODUCTION DYNAMICS

T. K. Roy[1*], M. A. Biswas[2], M. A. Sweety[3], S.M.M. S. Tonmoy[2], M. A. Rahman[4], T. P. Suvo[5], S. M. A. Alim[6] and A. Sannal[7]

[1]Entomology Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh
[2]Farm Management Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh
[3]Assistant Director, Bangladesh Agriculture Development Corporation (BADC), Dhaka, Bangladesh
[4]Genetic Resource and Seed Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh
[5]Soil Science Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh
[6]Plant Breeding Division, Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh, Bangladesh
[7]Plant Pathology Division, Gazipur Agricultural University (GAU), Gazipur, Bangladesh

*Corresponding author: tapon.entom@brri.gov.bd; taponroy.brri@gmail.com

ABSTRACT

Rice is the cornerstone of Bangladesh's food system, culture and tradition, daily life, employment and economy, which is sustaining more than 170 million people and shaping national identity for centuries. However, the long term sustainability of rice production is increasingly challenged by climate variability, resource constraints and nutritional limitations, necessitating a comprehensive synthesis of its current status and future direction. Present review synthesis the cultural heritage, dynamics of production and future prospects of rice in Bangladesh by integrating nutritional, agronomic, socio-cultural and abiotic-biotic perspectives. Rice is deeply associated in cultural traditions, festivals and livelihoods, while also serving as the primary source of dietary energy and significant contributor of protein and micronutrients in Bangladesh. The historical evolution of rice cultivars; indigenous landraces decrease and widespread adoption of high yielding varieties (HYV) and hybrids in diverse ecosystems. Some of them are stress tolerant has driven remarkable gains in productivity and food self-sufficiency. Moreover, the improvement of zinc, vitamin E, antioxidant, iron enriched and diabetic bio-fortified rice contribute to recover from malnutrition. The production increased from 9.77 MT (1971) to 40.62 MT (2024) within 54 years and average yield more than doubled (1.50 to 3.54 t ha^{-1}) due to HYV, improved irrigation, government policy (subsidy for fertilizer, electricity for irrigation, seed). Although, Aman (monsoon) season cover more area than Aus (pre-monsoon), and Boro (irrigated), but total production is high in Boro season due to improved management & irrigation. Despite achievement, rice cultivation faced multifaceted challenges, including abiotic stresses (salinity, flash flood, submergence, drought, temperature), biotic pressures (insect pests, diseases, weeds) and socio-economic constraints till now. Rice based crop diversification (integration of legumes, oilseed and vegetable), varietal diversification (use of stress tolerant, bio-fortified and specialty rice) can enhance system resilience, nutritional security and farmer income. The future of rice cultivation in Bangladesh depends on enhancing abiotic and biotic resilience through climate smart varieties, integrated pest management, mechanization and supportive policies, alongside diversification, value addition and sustainable resource use to ensuring long-term food security and socio-economic stability.

Keywords: abiotic stress; biotic stress; nutrition value; stress resilient; local landraces; perennial rice

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INTRODUCTION

Rice (*Oryza sativa* L.) cultivation in Bangladesh is not only for fulfill of food demand, but also playing a central role in national food systems, it embodies cultural identity, economic stability as well as national food security. The rice-based agriculture cropping pattern of the nation supports the livelihood of millions and underpins dietary energy supply, contributing 65-70% of daily caloric intake (FAO, 2025; Kamruzzaman *et al.*, 2025). Among the cultivated food grains in the country rice along contribute 97% of total grains (BBS, 2022; Rahman *et al*., 2023). So, the centrality in the national diet has made rice a critical pillar for food security of the nations. According to Bangladesh Bureau of Statistics (BBS, 2022), national estimates of rice growing area and rice production during 2022-23 is 28.75 million acres and 39.09 million tons, respectively and which secured 3rd largest rice growing country among the world just behind China and India. This high level of production is attributed to the adoption of modern high-yielding rice varieties, sustained growth driven by technological adoption, expansion of irrigation systems and supportive agricultural policies.

Approximately 76% of the total cropped area occupied by rice (15.44 million hectare), and of which 88% areas covered by modern rice varieties and 12% by traditional landraces (BBS, 2022). The sector directly or indirectly supports nearly half of the rural workforce (Rahman *et al.*, 2023), reflecting economic and social importance. The rice cultivation dominancy in agricultural land use reflects not only the climatic excellence of Bangladesh fertile floodplain soils but also the historical prioritization of rice in policy of national agriculture and traditional rural livelihoods.

The production system of rice in Bangladesh is characterized by three rice growing seasons: Aus (pre-monsoon rice: from April to July), Aman (monsoon rice: from July to November) and Boro (irrigated rice: from December to May). Where each season represents with unique sowing and harvesting patterns that help to make stable the annual output with accommodate climatic variability. However, maintaining this stability is challenged by various biophysical, natural climatic pressures, socio-economic importance, biotic and abiotic stress (Roy *et al.*, 2024; Rana *et al.*, 2025). Moreover, the expansion of rice production area is reduced by competing land uses, industrialization, urbanization and environmental degradation. As a results, the cultivable land is converted to non-agricultural land at a rate 0.29% annually (Parven *et al.*, 2022). Furthermore, change of climate including altered rainfall patterns, heat and cold stress, salinity and water stagnant stress, and resource scarcity introduces substantial uncertainty which threatening yield stability.

Rice based diets presents nutritional limitations due to heavy reliance despite crucial role of rice in food supply. Although rice is an efficient source of energy, it is relatively lower in essential micronutrient such as iron, zinc and vitamins, contributing to persistent public health concerns including anemia and stunting (Tripathy, 2017; Kamruzzaman *et al.*, 2025). The nutritional profile enhancement of rice through bio-fortification and the breeding of nutrient rich varieties highlights the importance of reducing dietary gaps without disrupting traditional food practices. While many studies have conducted about production of rice, consumption patterns and technological advancement in Bangladesh, existing literature often treats these dimensions in isolation.

Looking forward, for ensuring rice remains a lifeline for Bangladesh will require a holistic integrative synthesis linking the historical evolution of rice cultivation with its cultural importance, nutritional improvement and contemporary production challenges under changing climatic conditions. Moreover, previous literatures frequently emphasize production metrics without adequately addressing the interconnected roles of dietary dependence, sustainability constraints and emerging risks to food production systems. To address these gaps, our present review focuses on comprehensive and interdisciplinary assessment of rice in Bangladesh by integrating its historical development, socio-cultural relevance, nutritional and economic importance and present production status. It further evaluates the implications of these factors for food security and trade, with particular emphasis on emerging challenges and future research directions aimed at ensuring sustainable rice production systems. Therefore, a systemic available literature search was carried out to find relevant studies regarding nutritional status, history of rice, cultural heritage in Bangladesh, as well as status of rice production. For that purpose, reputable scientific databases like Scopus, google scholar, PubMed, WoS and Science Direct was thoroughly analyzed. All search employed a combination of the “rice in Bangladesh,” “rice cultural heritage in Bangladesh,” “nutritional status of rice,” “by-product of rice,” “local landraces in Bangladesh,” “rice varieties in Bangladesh,” “constrains in rice production in Bangladesh,” and “status of rice production in Bangladesh.” Furthermore, studies were confined from 2005 to 2026 time period and determined to peer-reviewed articles. Total 142 articles were collected from all the database. Finally, articles were chosen based on predetermined criteria after being screened for titles, abstract and duplicates relevancy. In the end this study included 87 articles (Table 1).

Table 1: Inclusion and exclusion criteria applied during literature selection

Criteria	Inclusion Criteria	Exclusion criteria
Publication type	Peer reviewed journal articles, review papers, conference abstract and scientific reports	Thesis, editorial and non-scientific publication
Publication period	Studies published between 2005 to 2026	Studies published before 2005
Focus	Bangladesh rice research, cultural heritage, rice production, landraces related with Bangladesh and rice research and nutritional value of rice	Studies not aligned with rice research
Accessibility	Full text articles with sufficient methodological and scientific information	Articles with unavailable full text or insufficient information
Records	Records included 87 articles out of 142.	Records excluded 55 articles out of 142 due to irrelevance.

Rice in traditional culture and socio-economic significance in Bangladesh: Rice consumption in Bangladesh is deeply associated with dietary patterns, social customs, language and traditions. Rice contributes the majority of caloric intake with per capita consumption from national food consumption data and estimated at approximately 144.50 kg $year^{-1}$, underscoring its economic and nutritional importance (Kamruzzaman *et al.*, 2025). Unlike diversified dietary systems seen in many regions of the world, food consumption behavior remains highly rice centric in Bangladesh, with most households consuming rice based meals multiple times (3 times) per day. Rice consumption in Bangladesh actually in every meal through streamed rice as khichuri, pulao, biryani, payes in myriad traditional desserts like puffed rice, flattened rice, parched rice, rice flour for making rice pitha (traditional rice cake) etc. Such consumption patterns are closely associated to levels of income, price stability, and food security policies, particularly for low-income populations where rice affordability directly influences caloric sufficiency (Hossain, 2019).

Beyond dietary role, rice is embedded in socio-cultural practices. Linguistically, “anna” the Bengali word represents with both rice and meal, revealing the semantic integration of rice into human nourishment and societal language; enlightening that eating rice is the same as eating food (Sengupta, 2010). “Have you eaten rice?” is a linguistic distinction that emphasizes the cultural significance and depth of rice. Rice related cultural practices are frequently aligned with seasonal production systems and agricultural cycles. For instance, the aman rice harvest during Bengali month Agrahayana (November-December) is linked to new rice harvest related festivals in rural Bangladesh popularly known as “Nabanna”, which associated with symbolize agriculture prosperity and community harmony (Showly, 2022). Similar to this, traditional rice based sweets, candies, cakes, and delicacies are prepared for seasonal festival (winter) like ‘Poush Parbon’ which highlight the significance role of rice in Bengali cultural heritage during the month of Poush (December-January). These rituals are more than just cultural manifestation; they represent link agricultural cycles with social rhythm and identity, especially among the rural communities where harvest cycles structure communal activities and belief systems (Sarker, 2024). Boiled rice, *khichuri, pulao* and fermented rice (*panta-vat*) are examples of rice based culinary products that further highlight the diversity of rice utilization and its adaptation to different socio-economic circumstances. For instance, *panta-vat* (fermented rice: boiled rice steeped in cold water overnight) consumption with fish during “Pohela Boishakh” (1st day of Bengali new year; 14th April) reflects both cultural identity and low-cost dietary practices suitable for warm climates (Showly, 2022). Similarly, ceremonial practices such as *annaprashan* or *akikha* or *mukhe-vat* (first rice feeding ceremony) demonstrate the symbolic importance of rice in life-cycle.

The socio-cultural importance of rice is further reflected in the preference for specific local varieties such as Kalijira, Chinigura, Tulshimala and Binni which are valued for aroma, grain quality and suitability for traditional dishes like Biryani, Payes and Kheer. Likewise, Tulsimala rice is socially embedded in weeding traditions in Sherpur district, where its serving to guests reinforces social bonds and to show familial honor. These varieties often command premium market prices and are associated with niche markets, thereby contributing to rural income diversification, particularly in smallholder farming (Showly, 2022).

Bangladesh’s rural economy and national development are based on rice. Approximately 77% of the total cropped area are covered by rice and contribute about 46% to the agricultural GDP and nearly 5% of the national GDP, which highlights its overwhelming economic weight (Nayak & Das, 2020). The rural livelihoods are closely associated to rice cultivation as a main source of income and employment. Rice based farming systems also support employment for millions of rural households are employed by rice based farming systems, which significantly influences labor markets, input supply chains and dynamics of rural development (BBS, 2022). Importantly, integrated farming methods and diversified cropping systems are supported by rice growing. Short duration crops like mustard (*Brassica juncea*, L.), potato (*Solanum tuberosum*, L.), onion (*Allium cepa* L.), garlic (*A. sativum*, L.), beans, oil crops, vegetables are cultivated between two rice growing seasons. Which, improves land use efficiency and stability of farm income. Moreover, integrated system likes rice-fish farming, further demonstrate the multi functionality of rice ecosystems provide food and nutritional security. These culturally embedded practices highlight that rice is not merely sustenance but a socio symbolic artifact which linked to collective memory, identity and communicative practices in Bangladesh.

Rice and its byproducts are used not only for human consumption but also contribute to livestock feeding and agro industrial sectors. From total production of rice, less than 1.8% is used as animal feed, based on the food balance sheet (Mohidem *et al.*, 2022). Based on rice production and rice straw, the local farmers are rearing chicken, duck, goat, and cow. Rice byproducts such as rice husks, broken rice, rice straw, rice germ and rice bran are widely utilized in animal feed manufacturing, production of bioenergy, industrial applications (Mohidem *et al.*, 2022), oil and cosmetic industries. Beside these, several byproducts come from rice; some common are rice noodles, rice bran oil, puffed rice, rice cake, rice flour, flattened rice, rice vinegar and rice crackers. This highlights the role of rice value chains in supporting circular bio economy approaches and reducing agricultural waste.

Despite socio-economic importance of rice, the heavy reliance on its raises critical policy concerns related to sustainability, dietary diversification and climate resilience. Furthermore, strong cultural and consumption preferences for rice may limit dietary diversification efforts, posing challenges for nutritional security. Therefore, future agricultural policies must balance the cultural significance of rice with need for sustainable intensification and diversification of food systems.

The nutritional value of rice and its role in human diets: Nutrition is a fundamental requirement for all living things to carry out essential functions including growth, development and production. The status of different types of nutrients varied across diverse rice varieties and types (Table 2). Rice is the most crucial source of calories, protein (7-10%), carbohydrate (about 80%), fat, fiber, copper, zine, phosphorus, vitamins, lipids (less than 1%) and to a lesser degree iron and potassium (Sitaresmi *et al.,* 2023; Wu *et al.,* 2023; Meharg *et al.,* 2024). Rice grains consist of three main components: the husk (outer protective layer), the bran layer (rich in fiber, lipids and micronutrients) and the endosperm (primarily composed of starch). Milling removes the husk and bran, producing white rice (the most popular rice type) which has a longer shelf life but reduced nutritional value compared to other types (Wu *et al.,* 2023; Kamruzzaman *et al.,* 2025). Brown rice is the most nutrient dense rice which contains vitamins (particularly B-complex and E), fiber and minerals (Table 2) due to retaining the germ, endosperm and bran (Wu *et al.,* 2023). According to Wu *et al.* (2023) parboiled rice, which is processed by soaking, streaming and drying before milling, retains some nutritious within the endosperm due to starch gelatinization and diffusion processes, thereby offering intermediate nutritional value between brown and white rice (Table 2). In addition, rice bran even after being removed during the milling process, still an important source of vitamins, minerals and fiber, which is used in foods to enhance their nutritional value like yogurt.

Starch is the dominant macronutrient in rice and consists of two major polysaccharides; amylose (linear chains of α-1, 4 linked glucose units) and amylopectin (highly branched structure) (Cornejo-Ramírez *et al.,* 2018). Amylopectin typically makes up 70-80% of total starch, while amylose content varies among cultivars and influences digestion and cooking quality (Farooq & Yu, 2025). Although processing, cooking methods and individual metabolic response affects the glycemic index (GI), rice varieties with higher amylose content often tend to have a lower glycemic response due to slower digestion. Low GI rice is another name diabetic rice, and some diabetic rice varieties also available in Bangladesh (Table 3). Although low GI rice varieties may help for glycemic control; their role in managing type 2 diabetes should be considered within broader context of food and lifestyle (Kader *et al.,* 2024). As a staple food for more than half of the global population, rice plays a leading role in ensuring food and nutritional security, particularly in Asia and developing countries (Sitaresmi *et al.,* 2023; Meharg *et al.,* 2024). The primary contribution of rice is to the human diet as a major source of energy, largely due to its high carbohydrate content, which typically accounts for approximately 75-80% of its dry weight. In addition, rice provides moderate amounts of protein (approximately 6-10%), small quantities of lipids (<1%), and essential micronutrients such as zinc, iron, phosphorus, and B vitamins, although these vary significantly depending on the rice type and degree of processing (Wu *et al.,* 2023; Kamruzzaman *et al.,* 2025).

Rice is generally low in micronutrients compared to diversified diets. However, its micronutrient intake plays crucial roles in populations with limited dietary diversity. Deficiencies in zinc and iron are widespread in many rice dependent regions and are associated with impaired immune function, growth retardation, diarrhea and anemia (Brown *et al.,* 2009; Gupta *et al.,* 2020). Numerous promising rice varieties (Table 3), enriched with essential micronutrient (like iron, zinc and β-carotene) are developed in this country for fulfill the deficiency of micronutrient through bio-fortification. These bio-fortified rice successfully enhanced the nutritional content of staple foods for sustainable agricultural practice.

Rice, particularly pigmented and whole grain types, contains bioactive compounds including flavonoids, sterols, anthocyanins, tocopherols, terpenoids, oryzanol and tocotrienols, rice also contains phenolic substances such as phytotic acid and phenols. These compounds have demonstrated antioxidant properties and are responsible to prevent cardiovascular disease and diabetes (Mohidem *et al.,* 2022). Rice exhibits anticancer, antioxidant and cholesterol lowering properties through various mechanisms, including γ-oryzanol (Cho *et al.,* 2019) antiapoptotic activity, anti-inflammatory effects, and chemoprotective actions (Sapwarobol *et al.,* 2021). The phytosterol ferulates found in rice are beneficial to human health in various ways. For example, cycloartenyl ferulate and 24-methylenecycloartanyl ferulate have antioxidative activity reduces cholesterol and cancer risk (Kim *et al.,* 2015), campesteryl ferulate and sitosteryl ferulate aid in reducing cholesterol synthesis (Berger *et al.,* 2005).

Rice is a staple meal which is perfectly fit for the Bangladeshi diet due to its high carbohydrate content, vast climatic adaptability and versatile cooking. The daily dietary needs for essential nutrient in Bangladesh are not frequently fulfilled, despite effort to incorporate to include nutrient from fruits, vegetables, legumes, beans and meats. Improving the nutritional value of rice can have a favorable effect on public health in Bangladesh, especially for low-income households that's depends largely on rice due to limited access to other food sources (HIES, 2023). Additional phytoactive compounds found in rice bran have also been reported to exhibit various pharmaceutical activities such as antidiabetic effects, anti-inflammatory properties, antihypertensive effects, cholesterol-lowering capabilities, antioxidant effects, and antimicrobial properties, underscoring the medicinal relevance of rice bran in contemporary times; it has been reported that in mice fed a high-fat diet, red rice bran extract alleviates various pathological complications associated with hepatosteatosis and dyslipidemia by modulating the expression of several key genes involved in oxidative stress, apoptosis, lipid metabolism and inflammation (Spaggiari *et al.,* 2021)

Table 2: Status of nutrient of different types of rice

Nutrient per 100 g rice	Parboiled rice	Brown rice	White rice (milled)	Rice bran
Calories (kcal/100 g)	374.00	363.00 – 385.00	349.00 – 373.00	399.00 – 476.00
Protein (g/100g)	7.51	7.10 – 8.30	6.30 – 7.10	11.30 – 14.90
Carbohydrate (g/100g)	80.9	73.00 – 76.00	77.00 – 78.00	34.00 – 62.00
Dietary fiber (g/100g)	1.80	0.60 – 1.00	0.20 – 0.50	7.00–11.40
Fat (g/100g)	1.03	1.60 – 2.80	0.30 – 0.50	15.00 – 19.70
Moisture (g/100g)	9.86	9.82	11.62	–
Calcium (mg/100 g)	71.00	10.00 – 50.00	10.00 –30.00	30.00 – 120.00
Iron (mg/100 g)	0.74	0.70 – 5.40	0.20 – 2.70	8.60 – 43.00
Potassium (mg/100 g)	174.00	120.00 – 340.00	14.00 – 120.00	–
Magnesium (mg/100 g)	27.00	1.30 – 4.20	1.00 – 3.30	–
Sodium (mg/100 g)	2.00	3.10 – 17.60	2.20 – 8.50	–
Vitamin B1 (thiamine) (mg/100 g)	0.22	0.29 – 0.61	0.02 – 0.11	1.20 – 2.40
Vitamin B2 (riboflavin) (mg/100 g)	0.05	0.04 – 0.14	0.02 – 0.06	0.18 – 0.43
Vitamin B3 (niacin) (mg/100 g)	5.05	3.50 – 5.30	1.30 – 2.40	26.70 – 49.90
Vitamin B6 (mg/100 g)	0.45	0.16	0.09	–
Vitamin B9 (folic Acid) (mg/100 g)	0.008	0.005	0.0002	–
Vitamin E (mg/100 g)	0.03	0.90 – 2.50	0.08 – 0.30	2.60 – 13.30

Source: (Wu *et al.*, 2023).

Table 3: Some nutrient enriched varieties with impact on health in Bangladesh

Name of rice Varieties	Special Feature	Amount	Impact on Health	References
BRRI dhan31	GABA enriched	-	GABA enriched, helps to reduce stress and improvement of sleep	(BRRI, 2023b; Kamruzzaman *et al.*, 2025; Tahsin *et al.*, 2025)
Biroi BR16 BRRI dhan46 BRRI dhan69 BRRI dhan105	GI (Diabetic) Rice	52.40 53.10 54.90 55.00 55.00	Low glycemic index, helpful for the management of blood sugar of diabetic patients	(BRRI, 2023b; Kader *et al.*, 2024; Kamruzzaman *et al.*, 2025; Tahsin *et al.*, 2025)
BRRI dhan42 BRRI dhan43 BRRI dhan62 BRRI dhan64 BRRI dhan72 BRRI dhan74 BRRI dhan84 BRRI dhan100 BRRI dhan102 BINA dhan20 BINA dhan28 BU dhan2 Nunia, Binaphul, Sagardhana, Hatisail, Kalobokra, Begun bichi Sakkorkhana	Zinc enriched	27.12 ppm 27.17 ppm 20.00 ppm 24.40 ppm 22.00 ppm 24.20 ppm 27.60 ppm 25.40 ppm 25.00 ppm 29.00 ppm 24.83 ppm 22.00 ppm - - - - - -	Improvement of zine intake, enhanced immune function and overall growth	(BRRI, 2023; Mottaleb *et al.*, 2025; Siddique *et al.*, 2025b)
BRRI dhan84 BINA dhan20 BU dhan2	Iron enriched	10.00 ppm 09.00 ppm 10.00 ppm	Improved iron intake and reduced risks of anemia	(BRRI, 2023b; Kamruzzaman *et al.*, 2025)
BR5	antioxidant	-	Enriched with antioxidant, aromatic rice, helps to reduce oxidative stress	(BRRI, 2023b)
BRRI dhan115	Vitamin E and antioxidant	14.98 ppm	Improvement of immune function, anti-ageing, protect from harmful effects of free radical	(BRKB, 2026)

Footnote: GABA:gamma-aminobutyric acid; GI: glycemic index; BRRI: Bangladesh Rice Research Institute; BINA: Bangladesh Institute of Nuclear Agriculture; BR: Bangladesh Rice; BU: Gazipur Agricultural University; ppm: parts per million

History of Rice Cultivars in Bangladesh: *Oryza sativa*, commonly known as Asian rice, has a domestication history. To understand the human-driven variation in modern rice cultivars, it is essential to first examine their ancestors, as the genus *Oryza* comprises 21 wild relatives of domesticated rice (Vaughan *et al.*, 2003). Japonica rice (*O. sativa* japonica) was originally cultivated in China 9,000 years ago (Fornasiero *et al.*, 2022) by the Neolithic people from the upper and lower Yangtze river valley, who were associated with pre-Austronesians and Hmong-Mien speakers, respectively (Chi & Hung, 2008; Bellwood, 2011; Hsieh *et al.*, 2011; He *et al.*, 2017). They also reported, as Neolithic farmers, traders and migrants traveled from China into South Asia specifically Bengal-Assam region via ancient routes, they brought rice grains with them and these imported Chinese rice hybridized extensively with native indica and wild aus landraces in the Bengal-Assam region. Indica rice likely emerged 4,500 years ago when japonica rice reached Indian sub-continent and hybridized with local wild or (*O. nivara*) proto-indica rice (Choi *et al.*, 2017). The evolution of rice cultivars in Bangladesh is primarily associated with *O. sativa*, particularly indica subspecies.

Although this global domestication narrative provides essential evolutionary context, the development of rice cultivars in Bangladesh is largely shaped by regional agro-ecological conditions and farmer led selection. Archaeological and historical evidence indicates that rice cultivation in the Bengal region dates back approximately 4,000 years, with continuous diversification driven by environmental heterogeneity and traditional farming practices (BRRI, 2023a). The region's vast river networks specifically Gangetic plains and the Brahmaputra valley, warm temperature, and lush alluvial plains have historically enabled intense rice production, which is the main source of income for residents (BRRI, 2023a). The predominance of indica rice in Bangladesh reflects its superior adaptation to tropical climates, while japonica types are limited to specific ecologies such as deep-water environments (BRRI, 2023a; IRRI, 2023).

Bangladesh has historically been one of the richest centers of rice genetic diversity. Although the exact number of pre-Green Revolution rice varieties is unknown, it is though that 15000 or so folk landraces flourished in Bengal in the 1940s (Debal, 2021). These landraces were developed through centuries of farmer led selection under diverse agro ecosystems, including flood prone lowlands, rainfed uplands, deep water ecosystems and saline coastal areas. As one of Asia's largest rice genetic resource repositories. Beside these, the BRRI Gene bank maintains 9,006 rice accessions under long-term storage, comprising 8,959 *O. sativa* accessions and 47 wild rice (*Oryza* spp.) accessions, of which 1817 accessions are of foreign origin (Siddique *et al.*, 2025a). This extensive genetic repository highlights the ecological and cultural significance of rice diversity in Bangladesh. Despite this richness, the adoption of indigenous varieties has declined significantly, with an estimated annual reduction of 4.50% from 1971 to 2019, due to the expansion of high yielding modern rice varieties (Rahman *et al.*, 2021). They maintain ecological and cultural resilience in addition to promoting food security. Rice continues to be a staple of the Bangladeshi diet, providing the average person with around 55% of their protein and 755 of their total calories (FAO, 2021). Throughout history, a variety of agro-ecological zones have supported the cultivation of distinct local landraces such as Bashful, Kalijira, Tepi Boro, Rajashail, Kataribhog, Kajolshail, Chinigura and Rajshahi Balam, which offer resilience against biotic and environmental challenges (Siddique *et al.*, 2025b). Rice cultivation in Bangladesh is closely linked to three major rice growing seasons; Aus, Aman and Boro, where each characterized by distinct environmental conditions. Traditional landraces are strongly associated with these seasonal ecologies. In Aman season local varieties like Rajashail, Gainja, Biroi, Gainda etc are adopted to rainfed and flood prone conditions. Whereas, Rata Boro and Tepi Boro are suited to irrigated dry season (Boro) cultivation. Popular aromatic local rice varieties like Chinigura (long-grain, traditional aromatic, popular for biryani), Kataribhog (better aroma, high yielding, unique texture and taste), Jirakatari (unique cooking qualities), Badshabhog (popular for its fragrance), Gobindobhog (aromatic rice widely used for its short grain), Kanakchur (fragrant variety, prized) and Kalizira (small grains, fragrant). Non-aromatic popular rice varieties like Nazirshail (slender grain), Miniket (very popular with its fine grain), Biroi, Lal Binni (unique texture with its red color), Gainja which are being used for daily consumption due to their grain characteristics (Islam *et al.*, 2024; Tahsin *et al.*, 2025). These rice varieties reflect a balance between subsistence demands, market need, and ecological adaption. The indigenous rice varieties are grown in Bangladesh's particular strees-prone region because of their physiological traits and capacity to withstand stress (Table 4).

Beside these special traits, local landraces have biotic and abiotic stress tolerance capability (Table 4). Significant amounts of accessions show tolerance to abiotic stresses, particularly salinity, submergence, cold and heat (Table 4). Some local varieties have valuable traits include higher protein content, anaerobic germination tolerance, popping quality and allelopathic activity (Rahaman *et al.*, 2021). Biotic stress resistance is widely distributed across traditional landraces, with notable clustering of resistance to major diseases such as blast, sheath blight and bacterial blight. Varieties such as Kataktara, Dular and Kataribhog repeatedly appear across multiple resistance categories, indicating their potential as valuable genetic resources for breeding programs. Similarly, resistance to insect pests such as stem borer, brown planthopper and green leafhopper are evident in several traditional cultivars (Table 4). Salinity tolerance is predominantly found in coastal rice landraces including Pokkali, Nonabokra and Latisail, while submergence tolerance is associated with deep water rice landraces like Sada Gabura and Kaladhan. Drought tolerance is observed among upland varieties such as Dular and Hashikalmi. These patterns highlight the role of environmental gradients influence genetic adaptability.

Importantly, these qualities have been incorporated through breeding programs into modern improved varieties like BRRI dhan51, BRRI dhan52, BRRI dhan56, BRRI dhan67, BRRI dhan79, BRRI dhan110, demonstrating the continuous relevance of traditional germplasm (Table 4). Moreover, functional and quality traits are strongly represented in indigenous landraces high protein landraces (Hashikalmi, Jamaibhog), allelopathic landraces (Kartiksail, Rajasail) and specialty types with popping quality or aromatic characteristics show multifunctional value beyond yield.

Table 4: Tolerance of biotic stresses and abiotic stresses, quality and special traits found in local rice landraces and modern varieties

Stress Type/Traits	**Representative Landraces**
A. Biotic Stress Resistance	
Blast	Kataktara, Dular, DNJ 60, Shamraj, Malshira, Betu, BRRI dhan114, BRRI dhan117, BINA dhan27
Stem rot	Betu, Ghigoj, Hashikalmi, Dular, Kataribhog
Sheath blight	Kataktara, Katiksail, Chinigura, Murali, Kalijira, Dudhkalam, Charnock, Sada pankaich, Mogail balam, Kalamanik, Hasa, Chinigura, Kalagura, Holud jaron, Hashful, Koia, Kalamona, Kumragoir, Lohagor
Bacterial blight	Khama, Gabura, Lal Khama, Akhnisail, Ratasail, Tulsimala, Kalagura, Hashful, Laida, Lal Khama, Kachamota, Kalosail, Hashikalmi, Maloti, Bara bazal, Chiknal, Hargaza, Ghunsi, BRRI dhan101, BINA dhan26
Ufra	Gabura, Rayada series, Indrasail, Hatisail, Modhusail, Jessobalam, Nizersail, Dhepi, Kumari, Lal aman, Jhingasail, Nizersail, Pankaij, Baish binni, Dudsar, Badshabhog, Holidjaran, Daudin, Rajasail, Modhusail, Bhawalia aman
Bakanae	Panati, Nizersail (DA 25)
Bacterial Leaf Streak	Hashikalmi
Rice tungro virus	Kataribhog, Latisail, Sada Pankaich, Badshabhog, Lakshmijota, Tilockachari, Soloi, Hbj. aman viii, Tulsimanik, Badariota, Noroi, Shirtsail, Mi-pajang and Jatramotor
Green leafhopper	Dular, Jhingasail, Morium, DNJ 97, Khorma, Godalaki, Aswina, Dumai, Hasmita, Gadur, Golapi, Sailbinni, Suna digha (2), Ashajus, Hasmita
Brown planthopper	Bara bazal, Balam, Rajasail 21, Dudsar, Bara bajal, Malia bhangor, Tangul, Digha, Krishnachura, Sungwala
Stem borer	Badshabhog, Latisail, Tulsimala, Joya, Rajasail, Bhasamanik, Rghusail, Botai, Kali boro, Aghnisail, Boilam, Jhoria, Murari
White-backed planthopper	Begum bichi, Khama 49/8, Lal dhan, Boira aman, Kalaraj, Bajal, Tara bali, Khawrang, Malia bhangor
Gall midge	Muktahar, Safahar, Koha binni, Vellutha cheera, BRRI dhan33
B. Abiotic Stress Tolerance	
Submergence	Sada gabura, Kalojoma, Kaladhan, Lohatang, Kumri, Hijaldigha, Kumragoir, Khoia motor, Soitedhora, Kaliraj, Putidepa, Laldepa, Songa Tepi, Ashfol, BRRI dhan51, BRRI dhan52, BRRI dhan79, BRRI dhan110, BINA dhan11, BINA dhan12, BINA dhan23
Tidal submergence	Dudmona, Kumragoir, BRRI dhan109
Anaerobic germination	Modhusail, Nizersail, Indrasail, Hatisail, Khirari, Lal aman, Ratasail, Dharial, Halid jaran, D. Lia and Chaita boro.
Drought	Chinisail, Dular, Hashikalmi, N sail, Canthi bakla, Hashim, Urichedra, Chini sail, Goura kajol, Boaincha biruin, and Sakkar khana, BRRI dhan56, BRRI dhan57, BRRI dhan66, BRRI dhan71, BRRI dhan83, BINA dhan17, BINA dhan19
Salinity	Rajasail, Kartiksail, Pokkali, Nonabokra, Reyasail, Noakhali, Nonakochi, Sabrimaloti, Molla digha, Bhawalia, Kumri aman, Neppasha, Banoi jhak (3), Bawoi jhak (6), Latisail, Patnai, Jota bhaulia, Halde midi, Lal bini, Lembur, Begun bichi, Khama rang, Ghori aman, Guda aman, Binni dhan, Boteswar, Bazal dhan, Chand moni, Sungwala, Lambra, Kala gura, Kolam, Lal kumara, BRRI dhan47, BRRI dhan67, BRRI dhan97, BRRI dhan99 BRRI dhan112, BRRI hybrid dhan9, BINA dhan8, BINA dhan10, BINA dhan23
Lodging	BRRI hybrid dhan9, BRRI hybrid dhan10
C. Quality and Special Traits	
Protein enriched	Hashikalmi, Jamaibhog, Dular, Baha bhog, Thakurbhog, Ashfol, Habigonj boro ii, Birani dhan, Jira dhan, Horkoch, Joyosri, Laltupi, Neda, Boilam, Molladigha, Matichak, Magoibalam, Lema, Niamat, Chakil, Banjira, Ghunsi, Kartikjhul, Apchaya, Holid jaran, Arichadigha and Manikdigha.
Popping quality	Rangabinni, Nizersail, and Kanakchul
Allelopathy	Kartiksail, Rajasail, Jhingasail, Kataribhog, Chakulia, Shada dumra, Bolorum, Burikatari, Joli, Kola dama, Biruin (tola), Mi-chocho, Rangpuri (sada) and Balam dhan.

Although, modern rice varieties significantly contributed to national food security, but these varieties often lack the broad adaptive traits found in indigenous varieties. So, the integration of traditional landrace for development modern varieties through breeding programs has therefore become a key priority. Notably, several improved varieties released by BRRI, other institutes and university have successfully incorporated some stress tolerance traits from local landraces, particularly for salinity, submergence, drought, blight and blast tolerance.

Present status of rice production in Bangladesh: Cultivation of rice in Bangladesh has undergone a profound transformation over the past five decades, shifting from traditional subsistence farming to a highly intensified and technologically driven production system. However, modernization during and after the Green Revolution led to the replacements of indigenous landraces by high yielding varieties (HYVs), resulting in substantial productivity gains but also a significant erosion of genetic diversity. According to recent studies, mono-cropping and habitat destruction have caused over 5,000 local rice varieties in Bangladesh to either vanish or become severely endangered (BRRI, 2023a). This genetic erosion poses long term risks to breeding programs, particularly under increasing climate variability, salinity intrusion and flood susceptibility in coastal regions (IRRI, 2023). Nevertheless, molecular studies reveal that existing landraces still harbor significant genetic variability, offering valuable resources for future crop improvement (Siddique *et al.*, 2025a).

At the time of independence in 1971, Bangladesh's rice production system was characterized by low productivity, limited irrigation, and heavy reliance on rainfall dependent cropping systems particularly Aus and Aman seasons. Total rice production was approximately 9.77 million tons in fiscal year 1971–72 (Fig.1, Fig.2) from 9.28 million hectares, with minimal yield of approximately 1.5 t ha^{-1} (Alauddin *et al.*, 2025; BBS, 2025). The cropping pattern was dominated by Aus (pre-monsoon) and Aman (monsoon) seasons mostly depends on rain, while Boro (dry) cultivation remained minimal due to inadequate irrigation infrastructure. Consequently, domestic production was insufficient to meet demand, requiring annual imports 1.5-2.00 million tons and exposing the country to food insecurity, as exemplified by the famine in Bangladesh (Hossain, 2026).

The 1980s marked a turning point with the expansion of irrigation infrastructure and the dissemination of HYVs developed by Bangladesh Rice Research Institute (BRRI). BRRI released breakthrough varieties such as BR1 (Chandina), BR2 (Mala), and BR3 (Biplab). Particularly, BR3 became significant, playing a key role in 'BR-revolution' as it was successfully adopted across all three growing seasons: Aus, Aman, and Boro; highlighting the potential of modern varieties to transform productivity (Momin *et al.*, 2025).

The rapid adoption of HYVs transformed the rice sector, increasing their contribution to total production from less than one third (29%) in 1972–80 to 80–90% by the late 1990s (BBS, 2025). This transition period also witnessed by a major shift cropping patterns with irrigated Boro rice expanding significantly (more than double; less than 1.00 Mha in the early 1970s and over 2.5 Mha in the 1990s) and becoming the dominant contributor to national production while Aus (2.11 Mha) cultivation declined and Aman (5.78 Mha) relatively stable. The total production of rice in 1990-91 was almost double (17.79 MT: Aus 2.48 MT, Aman 9.17 MT & Boro 6.36 MT) and which was cultivated within 10.43 Mha land. Continued varietal development of BRRI, including widely adopted cultivars such as BR11 (1980) for transplanted Aman-became a mega variety occupying over 50% of Aman area and acted as a parent for many subsequent varieties; BR22, BR23, BR25 for Boro season; BR14, BR26 for irrigated Aman; Specialized varieties for stress-prone environments (deepwater, tidal, saline). Rice production exceeded 15 million tons for the first time in fiscal year 1986, indicating an important psychological and practical milestone (BBS, 2025). Over time, other high-yielding varieties like BRRI dhan28, BRRI dhan29, BRRI dhan47, BRRI dhan49, and BRRI dhan50 substantially improved nationwide productivity, stability, particularly under irrigated conditions.

Boro season expanded substantially from approximately 1.5 million hectares in 1980 to over 3.5 million hectares by 2000, pushed by irrigation expansion and availability of high-yielding varieties suited to the dry season (Fig. 2). Aman remained relatively stable in area but productivity increased by adoptions of modern varieties. By the late 1990s, the seasonal distribution had altered to: Aus ~10%, Aman ~40%, Boro ~50% of total production (Fig. 1) (BBS, 2025; Mainuddin et al., 2021).

Since the 2000s, rice production has continued to expand, supported by technological, institutional and policy interventions. Total production increased from approximately 25.09 MT (Aus 1.92 MT, Aman 11.25 MT & Boro 11.92 MT) from 10.66 Mha land (Aus 1.33 Mha, Aman 5.71 Mha and Boro 3.76 Mha) in 2000-01. BRRI dhan28 and BRRI dhan29, two popular Boro rice cultivars, those contributed to the growth rate of 15.89% during 1990 to 2000 (Chakrobarty *et al.*, 2021; BBS, 2022). The widespread adoption of BRRI dhan28 and BRRI dhan29 which was released in 1994 initiated a 'second silent Green Revolution' in Bangladesh, representing a technological breakthrough comparable to the release of BR3 in the 1970s. Cropping intensity-defined as cultivating multiple crops on the same land annually- jumped from 143% in 1971–72 to 198% by 2009-10 (Alauddin *et al.*, 2025).

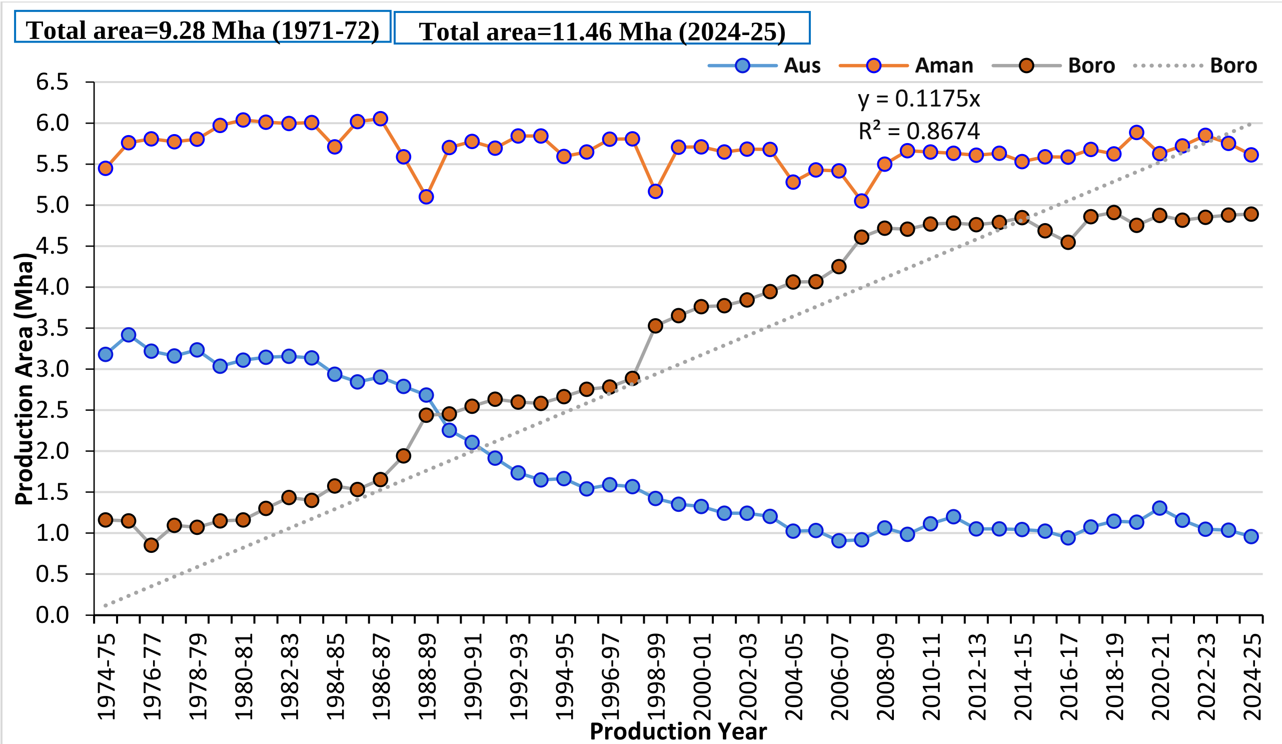

Fig.1: Trends in total rice production area in Bangladesh from1971-72 to 2024-25

Data source: (BBS, 2025)

A total of 33.54 MT (Aus 2.13 MT, Aman 12.79 MT & Boro 18.62 MT) rice was produced in 2010-11 season by cultivating 11.53 Mha land (Aus 1.11 Mha, Aman 5.65 Mha & Boro 4.77 Mha). From 2010 onward, BRRI shifted its research priorities toward more complex challenges like climate change mitigation, resource constraints, environmental sustainability, short-duration and stress-tolerant varieties, and bio-fortification of rice with zinc and vitamin A. Besides, the institute has invested in biotechnology, genomics, agronomy, pest management, farm mechanization, and socio-economic studies. Long-term trials of BRRI varieties indicates non-genetic factors (management, climate and irrigation) contributed to yield gains than genetic improvement alone, highlighting the role of agronomy and inputs alongside breeding (Rahman *et al.*, 2023).

Bangladesh first achieved self-sufficiency in 2008 when rice production was increased to 32 million tons from 27 million tons in 2000 due to the widespread adoption of high-yielding rice varieties (HYVs) and expanded irrigation catalyzed rapid production increases. The share of modern varieties in total production rose from about 29% in 1972–80 to nearly 90% by 2010, indicating intensive varietal substitution. Bangladesh has generally maintained this self-sufficiency in rice production status since 2012, producing 97–100% of domestic needs in most years. Between 1971 and 2024, production expanded from approximately 9.77 MT to 40.62 MT, and average yield more than doubled (1.50 to 3.54 t/ha) because of technological interventions, including high-yielding varieties (HYVs), increased use of irrigation, and better inputs propelled this growth. Government support and fertilizer/credit policy reforms also underpinned this expansion (Rahman *et al.*, 2023). By cultivation of 11.80 Mha (Aus 1.30 Mha, Aman 5.63 Mha & Boro 4.87 Mha) of land, total production of 2020-21 seasons was 39.18 MT (Aus 2.13 MT, Aman 12.79 MT & Boro 18.62 MT). A total of 40.62 MT (Aus 2.78 MT, Aman 16.51 MT & Boro 21.33 MT) rice was produced in 2024-25 season by cultivating 11.46 Mha land (Aus 0.96 Mha, Aman 5.61 Mha & Boro 4.89 Mha). Therefore, the production of rice increased by cultivating similar land and the Boro season is the dominating season in terms of production. The introduction of high yielding rice varieties (favorable and stress prone), improved agronomic management practice, government support for fuel, irrigation, fertilizer and mechanization, improved credit policies, increased quality seed supply, well organized fertilizer supply are the key factor for this improvement.

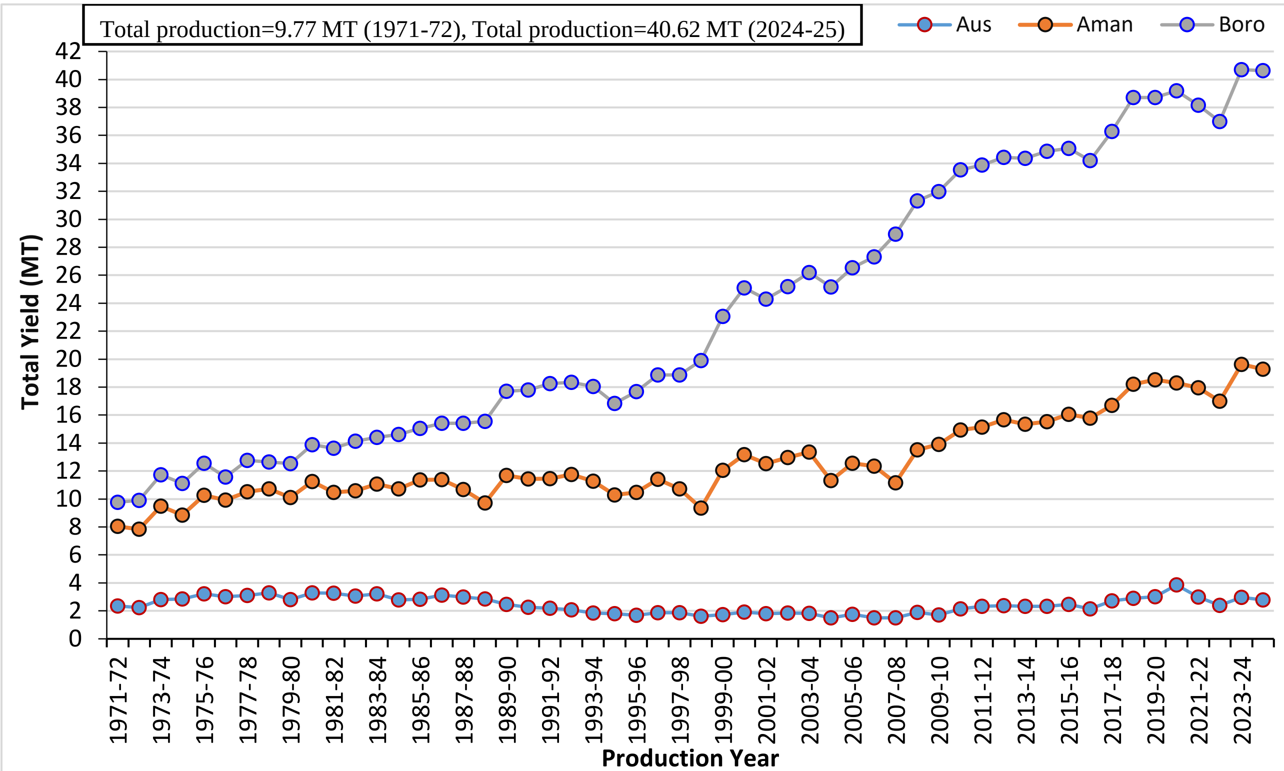

Fig.2: Trends in total rice production in Bangladesh from1971-72 to 2024-25

Data source: (BBS, 2025)

In recent years, research priorities have shifted toward sustainability and climate resilience. BRRI has developed 127 new high-yielding varieties, among which 117 are inbreeds and rest 10 are hybrid varieties. BRRI has developed 39 stress tolerant varieties, such as blast resistant, salt-tolerant, drought-tolerant, waterlogging-tolerant, cold-tolerant, and tide-tolerant varieties to resist the geographical diversity of Bangladesh, such as drought in the north, salinity in the south, flood and waterlogging in the central region. Advances in biotechnology, crop management and mechanization have further supported productivity improvements Overall, the evolution of rice cultivation in Bangladesh illustrates a successful transition from subsistence to semi-intensive agriculture.

Present status of local, HYV and hybrid rice production in Bangladesh: The production structure of rice in Bangladesh has undergone substantial transformation over the past decade, characterized by a steady decline in local landraces and a corresponding expansion of high yielding varieties and hybrid rice. The area covers by local landraces is decrease more than half now in both Aus, Aman (Supplementary Table 2) and Boro season (Supplementary Table 3). A linear trend assessment indicates that the area under local cultivars declined by approximately 76.50% in Aus (0.23 to 0.05 million ha), 49.36% in Aman (1.49 to 0.75 million ha) and 73.58% in Boro (0.05 to 0.01 million ha) from 2014-15 to 2024-25. This reduction of local landraces reflects a significant structural shift toward modern rice varieties. The area of local rice cultivars replaced by HYV in Aus and Aman seasons and hybrid in Boro season. The main cause of the local landraces decline are their comparatively lower yield potential and susceptibility to biotic and abiotic stresses. According to empirical data, HYVs can outperform traditional varieties by 20-50% in yield, depending on environment (Saha *et al.*, 2021; BRRI, 2023a). Additionally, improved irrigation infrastructure and the policy driven dissemination of modern rice varieties have accelerated this transition.

HYV cultivation remained dominant and relatively stable particularly in Aus, Aman and Boro seasons. Farmers often prioritize HYVs due to their stability, grain quality, lower input costs and can produce seeds by themselves. Conversely, the cultivation of hybrid rice is getting popularity during Boro season which replacing local landraces and HYVs. Adoption of hybrid rice exhibits a distinct seasonal pattern. In Aus and Aman seasons, hybrid rice remained negligible until recent years, contributing less than 5% of total area even by 2024-25. However, in the Boro seasons, hybrid rice expanded significantly, with cultivable area increasing from 0.69 to 1.29 million ha, representing an approximate

85.82% growth over the decade (Supplementary Table 3). The production areas covered by hybrid rice is almost double within 10 years. Consequently, the production of hybrid rice nearly doubled from 3.31 to 6.23 million metric tons, indicating higher productivity compared to conventional varieties.

Impacts of rice production on trade and food security in Bangladesh: Rice as the country's staple food, accounts for approximately 67.5% of daily caloric intake (Yunus *et al.,* 2019; FAO, 2021). Bangladesh as the third largest rice producer around world, the rice economy is intrinsically linked to national food security and socio economic stability. Secondary time series data from 1971-72 to 2024-25, long term analysis reveal that rice production has increased more than three and a half times over this period. To sustain national food security, Bangladesh needs to increase rice output by an additional 2.0 million tons annually, particularly as the population growth of over 2.2 million people each year (Saha *et al.,* 2021). Consequently, increasing agricultural efficiency and productivity remains a critical priority.

Rising demand for rice, coupled with decline in arable land, has intensified pressure on the production system. According to trend analyses, rice output increased gradually at an average annual rate of 0.6 million tons between 2009 and 2019; however, maintaining food security will require sustaining annual growth of at least 0.35 million tons. In contrast, cultivable land is decreasing at an approximately annual rate of 0.5% (Ullah & Uddin, 2021). Projections by (BRRI, 2023a) estimate that feeding a population of 210 million by 2050 will require around 47 million tons of rice.

Rice is cultivated on more than 150 million hectares land globally and remains economically vital, particularly in Asia, including Southeast Asia, China, and India (IRRI, 2023). Despite regional and cultural variations, rice is expected to remain a primary food source for over one-fifth of the global population in the coming decade, highlighting its importance for global food security (Fukagawa & Ziska, 2019). Although Bangladesh is largely self-sufficient in production of rice, but its trade dynamics are highly sensitive to domestic production variability and global market fluctuations. In years of production shortfall, Bangladesh imports significant quantities of rice from major exporters such as India, Thailand and Vietnam, conversely imports decline sharply in surplus years, demonstrating a reactive trade pattern rather than a stable export oriented system (FAO, 2021).

The rice market is highly segmented based on grain quality, size and aroma. Fine rice (length to width ratio > 3), medium rice, coarse rice (length to width ratio < 2.1) and aromatic varieties (imported basmati and jasmine or locally produced Chinigura and Kalijira) cater to different consumer preferences and income groups (Custodio *et al.,* 2016). Premium varieties such as Chinigura and Kalijira command higher market prices, reflecting strong consumer demand for quality attributes (Rahman *et al.,* 2021). However, hybrid rice often faces market interference due to perceived inferior grain quality, which limits its adoption despite higher yields. Rice price volatility in Bangladesh is influenced by multiple factors, including seasonal production variability, climatic variables, input cost fluctuations and global market trends. For example, as 15-25% domestic rice prices increased during supply shocks, particularly following extreme weather (Rahman *et al.,* 2021a). Additionally, the global rice market is relatively thin (only 10% of total production is traded internationally) making it highly susceptible to price volatility (Fukagawa & Ziska, 2019). Government interventions, including public procurement, buffer stock management, and subsidized distribution programs, play a critical role in stabilizing domestic markets and ensuring access for low-income populations. However, inefficiencies in procurement and storage infrastructure can limit the effectiveness of these interventions.

There are comprehensive rice value chain in Bangladesh, involving approximately 17,000 rice mills that converts paddy into either parboiled or non-parboiled rice. National consumption dominates by parboiled rice, although non-parboiled rice is preferred in specific regions, notably the western Khulna Division (Custodio *et al.,* 2016). Rice is typically distributed by wholesalers to retailers in 50 kg bags and sold to consumers in open markets either as loose grain or in sealed packages. Additionally, a separate public procurement system supports lower income households by purchasing paddy at premium prices and distributing rice through government programs and authorized outlets. The main byproduct of rice milling is rice husk, used as fuel for boilers in the mill, feeds for animal including cow and buffalo, poultry litter, biomass pellet, biochar production, silica nanoparticle, 3D printer filler, and many more industrial and agricultural purposes. Besides husk, rice bran is another byproduct from which rice bran oil manufactured. Many rice bran oil industries depend on rice mill for collection of rice bran. Besides oil rice bran also used in food industry, cosmetics industry (lotion, shampoo, sunscreens etc.) in Bangladesh.

Despite huge achievements, production of rice in Bangladesh faces substantial challenges due to climate change, including increasing coastal salinity, declining soil fertility, falling groundwater levels, reduced cultivable land, natural resource depletion, heightened pest and disease pressures, and vulnerability to floods and droughts.

Constraints of rice production in Bangladesh: Rice production in Bangladesh is intricately correlated on climatic variability and socio-economic factors, which making the system highly vulnerable to multiple stressors. The agro-ecosystems of Bangladesh depend heavily on rainfall distribution, temperature variations, hydrological dynamics, and soil conditions. However, its geographical location in a deltaic floodplain and increasing climate variability exacerbate risks to food security. To fulfil the existing demands of the production, the intensified application of chemical fertilizers contributes to elevated greenhouse gas emissions (GHG) and environmental degradation, thereby accelerating climate change, often described as climate forcing. These climatic alterations can adversely affect agricultural productivity. Among all sectors, agriculture is particularly vulnerable to climate change impacts, which manifest as erratic temperature and precipitation patterns, cyclonic events, unexpected and prolonged monsoon flooding and recurring droughts. Additionally, climate-induced sea-level rise is increasing soil and water salinity in southern regions, leading to a reduction in cultivable land. Climate model projections further suggest that Bangladesh will face notable rises in mean temperatures and more frequent extreme climatic events, including heatwaves, posing serious risks to crop and livestock production systems.

Rice's abiotic constraints: In order to secure rice production to fulfill the demands of an increasing population under changing climate, future rice must surely be environmentally resilient with a modest response and good in performance when cultivated under stress conditions. Each year, the agricultural sector suffers considerable damage from droughts, floods, cyclones, and extreme heat.

The world is getting wormer due to climate change. In comparison to preindustrial temperatures (1850-1900) the present global ambient temperature has risen by 1.2°C and it is expected to have approached 2.7°C by 2100, according to Inter-governmental Panel on Climate Change (IPCC, 2023). Since, rice is extremely sensitive to high temperatures from the seedling stage to the reproductive stage and yield loss will lead to 3.2% for every 1°C average increase temperature (Muehe *et al.*, 2019; Zhang *et al.*, 2023). The maximum critical limit of temperature is 35°C during reproductive stage at or above which temperature grain pollination and grain filling highly affected negatively. Extreme temperature, including heat stress during anthesis, reduce pollen viability and increase spikelet sterility, which limiting grain number and yield directly. Phytohormones such as brassinosteroids (BRs) plays crucial roles in rice's heat stress response is well established (Yang *et al.*, 2021; Zhang *et al.*, 2023), but its mechanism is still unknown. Heat stress induced spikelet degeneration and yield loss are caused by the increased breakdown of BRs in young panicle while BRs can suppress spikelet degeneration and enhance heat resistance by improving activity of root, canopy characteristics, energy and antioxidant status in young panicles (Zhang *et al.*, 2023).

Cold and chilling stress is another abiotic stress which significantly impacts the rice production in Bangladesh, particularly during Boro season in Haor and northern parts. The temperature during Boro season from seedling to maximum tillering stage is between 10-25°C (normally 10-15°C) and then gradually increased (Roy *et al.*, 2024). Cold and chilling stress induced poor germination of seed, stunted seedling growth, yellowing and increased spikelet sterility and ultimately affects yields. Biochemical, physiological, phenotypic, molecular and cellular understanding of chilling tolerance in rice's resistance to chilling as well as innovative strategies to expedite molecular design breeding for cold tolerance in rice varieties (Li *et al.*, 2022b). For development of cold and chilling tolerant rice varieties, advances in molecular biology have identified genes such as bHLH57, which played crucial role and can enhance trehalose synthesis, reactive oxygen species metabolism which acting as a positive regulator and can enhance seed setting rate and seed size thereby increasing grain yield (Li *et al.*, 2022a). Therefore, cold and chilling stress tolerance rice varieties development is very crucial including bHLH57 gene for these region with high grain and premium quality rice.

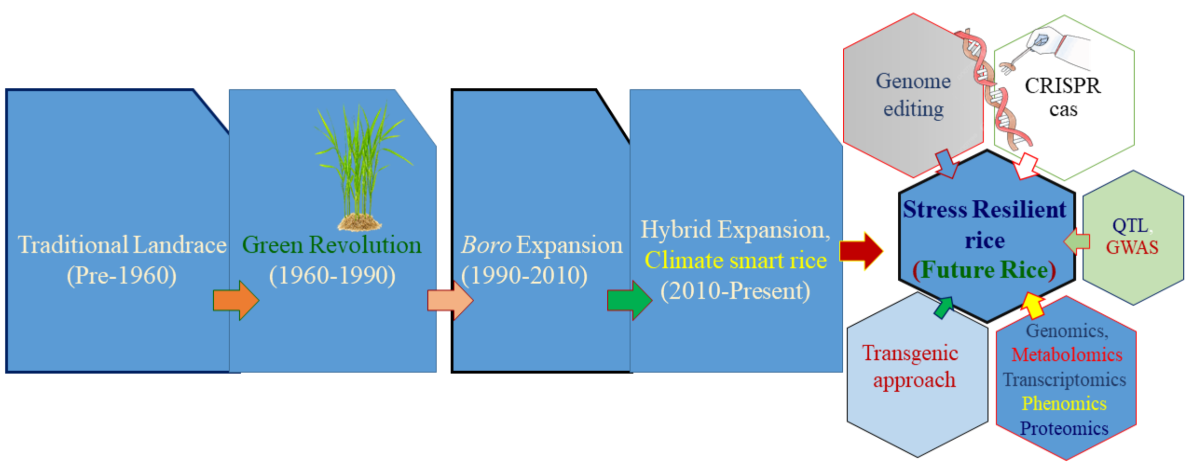

Fig. 3: Evaluation of rice cultivation in Bangladesh from green and early transformation to modernization and future stress resilient rice

Bangladesh is highly vulnerable to various natural hazards, among which flooding is the most recurrent and destructive. Approximately 80.2% of the country's land area is exposed to disaster-related crop losses, with land degradation attributed mainly to river and coastal erosion (68.3%), followed by flooding (14%), waterlogging (3.5%), and drought (0.8%) (Islam, 2016). Flooding in Bangladesh is increasing in both frequency and severity due to rising sea levels, especially in the low-lying coastal areas along the Bay of Bengal. A projected sea-level rise of 2 meters, together with a 15–25% increase in river flow, is expected to worsen flooding. If sea levels rise by 1.44 meters, about 16% of inhabited land could be flooded, around 13% of the population may be displaced and GDP could decline by 10% (Bhuiyan & Dutta, 2012). Moreover, flash flood is another constraint during Boro seasons in haor areas due to heavy rainfall of haor and Indian hilly areas during the summer, pre-monsoon and post-monsoon seasons. The haor wetlands, which constitute one of the country's major rice-growing zones, are especially susceptible to extreme climatic events, where repeated flash floods disrupt Boro rice cultivation and threaten the livelihoods of millions of people (Baishakhy *et al.*, 2023). Enhancing the development and adoption of flood resilient rice varieties could significantly improve the capacity to withstand natural disasters while protecting food security and rural livelihoods in Bangladesh. Submergence tolerant rice varieties with genes such as SUB1 have shown the ability to withstand up to 10-14 days of complete submergence, significantly reducing production losses in flood prone environments.

Drought is another major abiotic constraint affecting rain fed rice production in Bangladesh, with the northwest region experiencing particularly frequent and severe drought conditions (Mardy *et al.,* 2018). Among rice varieties, Aman rice plays a particularly important role but is also the most vulnerable to drought stress during its reproductive stage (Mahmood *et al.,* 2004). The impact of drought largely depends on the crop growth stage at which water stress occurs. Although rice plants can often tolerate and recover from moisture deficiency during the early seedling stage, water stress during later growth stages is far more detrimental (Dubey *et al.,* 2018). The reproductive phase is especially sensitive and even short-term water shortages at this stage can cause substantial yield losses, leading to economic hardship for farmers and increased risks of food shortages. Drought tolerant varieties incorporating quantitative loci (QTLs) such as qDTV, have shown yield advantages of 1-1.5 t ha^{-1} under water deficit conditions (Kumar *et al.,* 2014).

Saltwater intrusion also threatens freshwater resources, aquaculture and agriculture. Overall, sea-level rise and global warming are major challenges to agricultural development and poverty reduction in Bangladesh (Masud *et al.,* 2017). Salinity levels in coastal soils and water bodies rise markedly during the dry winter months and decline with the onset of the monsoon. Nearly one-fifth of Bangladesh's total land area lies within the coastal zone, of which about 30% is classified as net cultivable land (Haque, 2006). However, elevated salinity during the winter season renders a substantial portion of this land unsuitable for crop production. Aman rice dominates agricultural production in these coastal regions, where farmers mainly cultivate traditional rice varieties that possess some degree of salinity tolerance but are characterized by low yield potential. The progressive increase in salinity due to saltwater intrusion presents a serious challenge to coastal livelihoods and public health, affecting agricultural productivity, aquaculture, infrastructure, coastal ecosystems, and the availability of freshwater for domestic and commercial purposes.

Rice's biotic constraints: During rice cultivation process from seedling to maturity stages of rice plants, are infested easily by many insect pests and pathogen likes fungi, bacteria, virus and nematodes. Even during storage, it is also infested by various stored pests. Rice fields are infested by 232 harmful insects in Bangladesh and 20-25 identified as major insects and of them, significant grain loss by the infestation of stem borer, brown plant hopper, and rice leaf folder (Ali *et al.,* 2021; Roy *et al.,* 2024). Rice fields are infected by 32 diseases in Bangladesh, of which 22 fungal, 3 bacterial, 6 by nematodes, 1 by virus and 1 by mycoplasma (Khatun *et al.,* 2021). Rice blast, bacterial leaf blight, sheath blight, false smut, bakane and tungo are the major rice diseases and significant amount of yield losses by the infection these diseases every year. Advances in molecular breeding have enabled the incorporation of resistance genes (e.g., Xa, Pi genes) for blight and blast, yet field level effectiveness is often reduced due to pathogen evolution. Conversely, there are lack of proper storage facilities, that's why storage pests like angoumois grain moth, rice weevils damage significant amount of rice (Roy *et al.,* 2026). Rats another biotic constrains in both field and storage condition responsible for significant amount of rice. Sometimes birds also responsible for grain loss in early and late maturity stage of rice varieties. Weed infestations is another problem for rice cultivation. The rice fields need to keep weed free until maximum tillering stage. Although farmers are managing these pests through extensive application of pesticides, but this practice raises serious concerns in regarding environmental safety and human health. Moreover, due to overdose and improper use of pesticides has led to the development of resistance in pest populations. The farmers of Bangladesh often apply imbalanced fertilizer doses. They frequently used over or below dose of N fertilizer than the recommended dose, while P and K fertilizers are also not applied in balanced proportions.

Socio-economic constraints: Subsequently, Bangladesh is facing a steady decline in arable land, with an average annual loss approximately 72300 acres, representing nearly 0.29% of the country's total agricultural area (Ullah & Uddin, 2021). This decline is largely driven by the transformation of farmland into non-agricultural uses, particularly as a result of rapid urban expansion and related development activities. As a result, Bangladesh is losing close to 1% of its agricultural land each year (Quasem, 2011; Ullah & Uddin, 2021). Moreover, food security challenges in Bangladesh are intensified by limited access to modern agricultural technologies, inadequate mechanization, unstable market pricing, weak pest control measures, rapid population growth, and low levels of farmer awareness (Roy *et al.,* 2024). The supply of quality seed among farmers are still not adequate. The fundamental of healthy plant and high yields is mostly depends on good quality seed. Moreover, the hybrid rice cultivation increasing rapidly but the country seed producer are mostly depends on hybrid rice parental lines as well as seed import from China, India and other countries. The land of farmers are small where commercial mechanizations are not possible. Tackling these interrelated problems, now highly demands for an integrated approach that combines improved farming practices, capacity building, technological innovation, and sustainable management of natural resources. Another is mechanization, due to small land, mechanization yet not satisfactory. For that, the scarcity of labor often observed during full season.

Future prospects of rice cultivation: By 2050, the demand of rice worldwide will be about 584 million tons or less (Samal *et al.,* 2022) driven by population growth, urbanization and dietary preferences. Moreover, the rice value chains are evolving quickly in order to satisfy the demand for rice with high quality and attributes (such as taste, grain shape, smell, nutrition and others) in many parts of worlds as well as Bangladesh. So, to feed the increased population won't be easy. Therefore, making the current agrifood system efficient, sustainable, inclusive and resilient is of especially significance in food security, required to searching new rice variety with production systems. The rice agriculture will have changed due to positive technology advancements with times. The future rice development mostly depends on adopting climate resilient (drought, heatwaves, submergence, salinity etc.), high yielding, sustainable water and nutrient management and technology innovations to bridge the gaps of yields.

Short term priorities (0-5 years)-

- Dissemination and adoption of existing stress-tolerant and high-yielding rice varieties (e.g., submergence, and salinity tolerant cultivars).
- Improved agronomic practices, including optimized sowing dates, water-saving irrigation (e.g., alternate wetting and drying), and balanced nutrient management.
- To reduce pesticide dependency, need to expansion of integrated pest management (IPM) and ecological engineering approaches.
- By using digital platforms and remote sensing tools need to strength real time pest and climate advisory systems.

Medium term priorities (5-15 years):

- Development of multi stress tolerant rice varieties using marker assisted breeding, genomic selection, and gene pyramiding.
- Enhancement of rice nutritional quality via bio fortification (e.g., zinc, iron, vitamin A and antioxidant enriched rice).
- Integration of climate smart agriculture practices and mechanization to improve labor efficiency and reduce production costs.
- Strengthening rice value chains through improved storage, processing, and market linkages tailored to urban demand.

Long term priorities (15+ years):

- Deployment of advanced breeding technologies such as CRISPR/Cas genome editing and speed breeding for rapid varietal development.
- Development of "climate-resilient super rice" combining high yield, resource-use efficiency, and tolerance to multiple abiotic and biotic stresses (Fig. 4).
- Transition toward sustainable rice systems with reduced greenhouse gas emissions and improved ecosystem services.
- Diversification of cropping systems while maintaining rice productivity to ensure both food and nutritional security.

Rice abiotic resilience: The heat stress is emerging as an important factor for rice cultivation in Bangladesh. But there are no rice variety for heat resilience. BRs (brassinosteroids) mechanism can make plant heat stress resilience. So, future research should focus more on rice's ability to balance growth and heat stress response and discover BRs mechanism coupled with agronomic adjustment of sowing dates and microclimate manipulation.

Environment sensitive genic male sterility (ESGMS) which is a unique kind of male sterility and is influenced by environmental and genetic variables, may be useful for Bangladesh. The two-line hybrid rice breeding strategy is centered around ESGMS lines while they can be transferred into fertility as changes of corresponding environment (temperature, humidity, photoperiod and others). The use of the ESGMS line in rice hybrid breeding requires the cloning of ESGMS genes and the clarification of their underlying mechanisms. Future efforts to overcome bottlenecks that limit the application of ESGMS found in rice: TSGMS (thermal-sensitive GMS), PSGMS (photoperiod-sensitive GMS), NSGMS (nitrogen-sensitive GMS) and HSGMS (humidity-sensitive GMS) summarized by (Peng *et al.,* 2023; Shi *et al.,* 2023).

There is no doubt that environmental factors are complex and have synergistic impacts on rice cultivation at each rice growth and developmental stage and production. Presently, most of the relevant research has been conducted on a single stress in a controlled environment, very few conducted on multiple stresses or to a lesser extent in field based facilities. Additionally, molecular responses of rice to environmental variables mainly captured specific tissues at certain growth stage, rather capturing all tissues over the life cycle. So, there are still significant gaps between theoretical research and development of varieties, which prevents rice breeding from forming a positive feedback loop. So, new strategy and new tools are needed for fully understand the dynamic nature of rice environment interaction under real situation of fields. The development of DNA markers closely associated with target QTLs or genes has improved the accuracy and dependability of marker assisted gene pyramiding which combines known agronomically significant genes into a single elite genotype in rice (Haque *et al.,* 2021; Shi *et al.,* 2023). Although it is not simple to develop stress resistant rice varieties by using marker assisted breeding based on known QTLs or genes for high yield and stress resilience but is promising.

Hybridization between Asian and African rice or wild rice could be utilized to increase the environmental resilience of rice cultivation in Bangladesh. However, this would require new techniques in addition to cytoplasmic male sterile wild rice and embryo rescue in future. Future rice should be drought resistant and water saving, in order to save freshwater lower emissions of methane emissions from rice fields. Due to genetic trade-offs caused by tight connections or pleiotropic effects lowland rice is more productive but sensitive to drought while upland rice resistant to drought but less productive. By combining strong and various types of phenotypic selection with traditional pedigree breeding and marker assisted selection to achieve the required yield potential, water use efficiency and drought resilience (Shi *et al.,* 2023). Future food security mostly depends on by the pyramiding of green traits (nutrient efficiency, heat tolerance, cold tolerance, salt tolerance, disease and insect resistance) in drought resistance and water saving rice.

Rice biotic resilience: Significant progress has been made in developing disease resistant rice varieties in Bangladesh including bacterial leaf blight rice varieties such as BRRI dhan101 and BINA dhan26 and blast resistant rice varieties such as BRRI dhan114 and BRRI dhan117. Despite these advances, major constraints remain, particularly from sheath blight, stem borer, brown plant hopper and rice leaf folder. Synthetic pesticide applications are the only remedy commonly practice by the farmers. The applications of 3-5 times pesticides (Roy *et al.,* 2024; Shultana *et al.,* 2025) which is neither sustainable nor effective in the long term due to the development of pest resistance. Moreover, insects and disease are also changed their strain and behavior against these chemicals and getting resistant. So, extension of ecological engineering (Bari *et al.,* 2025) with integrated management system might be an alternative to reduce pesticide use. The inclusion of pheromone traps and natural enemies has enhanced integrated management with measurable reduction of insect pressure during rice cultivation.

Real time forecasting of pest using climate model and remote sensing can support decision enhancement systems, enable targeted actions and also reducing unnecessary inputs. Future biotic stress management research should focus on host plant resistance, precision surveillance and eco-friendly interventions (Roy *et al.,* 2025). Marker assisted breeding, genomic selection, anthers culture, CRISPR technology provide tools to pyramid multiple resistance genes against blast, bacterial leaf blight, sheath blight, planthoppers, stem borer and leaf folder etc. and it will be miracle if combing with abiotic stress (Fig. 4).

Fig. 4: Effects of biotic and abiotic stress on growth and yield performance of stress susceptible rice (current rice-left side) and stress tolerant rice (future rice-right side)

Others prospects: Although perennial rice is not popular in Bangladesh, but due to its more assimilate reserve and greater root systems it can be another alternative for cope with abiotic stress (Zhang *et al.*, 2022). So, future research needs to more focus on perennial rice with introgression of abiotic and biotic stress resistant gene (Fig. 4). The land of Bangladesh is small. In order to diversify risk and increase the price of product for smallholders, contact farming has become a popular vertical coordination mechanism. Production contracts can help smallholders to meet their financing, storage and transportation demands while also shifting the risk associated with farming. Contact farming, using future markets to manage commodity risk, and consumer-based market intelligence are other prospects that will benefit the farmers.

Conclusion: Rice is the lifeline of Bangladesh and closely linked with culture, tradition and daily life of Bengali people. Rice continues to dominate dietary intake, supplying the majority of caloric energy and a substantial proportion of protein, carbohydrate, vitamins and minerals people mostly depends on rice especially rural people. Rice production in Bangladesh stands at a turning point, where yield expectations, genetic diversity, climatic vulnerability and quality demands intersect together. Over the past decades, significant increases in rice production have been achieved through the widespread adoption of modern high yielding rice varieties, expansion of irrigated Boro rice cultivation and improved agronomic practices. However, this intensification has contributed to the erosion of traditional rice landraces. Despite notable progress, the sustainability of rice production is increasingly constrained by multiple interacting factors, including climate change induces stresses (e.g., salinity, drought, submergence and heat), emerging pest and disease pressures, declining soil health and socio-economic limitations such as labor scarcity, less mechanization and rising production costs. The future trajectory will mostly depend on harnessing genetic resource through the conservation and utilization of indigenous germplasm, combine with advanced breeding is essential for developing HYV, climate resilient and nutritionally enriched rice varieties. The adoption of precision agronomic management such as cite specific nutrient management, water saving irrigation can enhance productivity. Furthermore, bridging the gap between yield potential and grain quality, particularly in premium and export oriented markets with biotic and abiotic resistance requires interdisciplinary research, robust policy support with strong stakeholder engagement. Policy support should prioritize investment in research and development, farmer training, digital agriculture, and market infrastructure to ensure equitable access to technologies and fair pricing mechanisms. For ensuring sustainable food and nutritional security, Bangladesh can transform its rice systems into resilient, productive and quality oriented platforms with strategies innovation and investments in the decades ahead. So, future research should focus on climate resilient and stress tolerant rice breeding, nutritional enhancement through bio-fortification, sustainable intensification and resource use efficiency, socio economic analysis to support farmer adoption and system transformation.

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