Research Article

Strategic Irrigation Management Enhances Growth, Phenological Development, and Grain Yield in Bread Wheat (*Triticum aestivum* L.)

Muntarina Hussan Mouri[1,2], Mahadi Hasan Monshi[2,3*], Rehenuma Tabassum[1,4], Bright Gyamfi Adu[4], Hasan Mehraj[4], Md. Shakhawat Hossain[5], Jahidul Hassan[6], Ahmed Khairul Hasan[5] and Fakhrul Islam Monshi[4,7]

[1]Department of Crop Botany and Tea Production Technology, Sylhet Agricultural University, Sylhet-3100, Bangladesh; [2]Green Care Agro Farm Ltd., Debidwar, Comilla-3530, Bangladesh; [3]Department of Economics, University of Chittagong, Chittagong-4331, Bangladesh; [4]Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo-113-8657, Japan; [5]Department of Agronomy, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh; [6]Department of Horticulture, Gazipur Agricultural University, Gazipur-1706, Bangladesh; [7]Department of Genetics and Plant Breeding, Sylhet Agricultural University, Sylhet-3100, Bangladesh.

Abstract | Wheat (*Triticum aestivum* L.), a significant cereal crop in Bangladesh, confronts production challenges due to inadequate irrigation techniques and limited varietal adaptation, resulting in increasing dependency on imports. This study sought to assess the combined impacts of genotype and irrigation scheduling on agronomic traits, phenology, and wheat production in subtropical agroecological conditions. The experiment was conducted two-factor split-plot design with three replications during the 2024-2025 rabi season at Mymensingh, a representative wheat-growing area in Bangladesh, on seven wheat genotypes (Protiva, BARI Gom-19, -20, -22, -25, -30, and -32) under four irrigation regimes: no irrigation (I_0), a single irrigation at crown root initiation (CRI) (I_1), two irrigations at CRI and booting (I_2), and three irrigations at CRI, booting, and grain filling (I_3). Significant variation ($p < 0.001$) was observed for genotype, irrigation, and their interaction across twelve studied traits. Irrigation at three stages (I_3) significantly improved plant height, tiller number, spike length, grain weight, and harvest index. Among the varieties, BARI Gom-32 produced the highest grain yield (4.66 tha^{-1}) along with the highest plant height (95.11 cm), length of spike (13.25 cm), number of grains $spike^{-1}$ (49.76), thousand grain weight (51.39 g), and harvest index (54.38 %). Conversely, Protiva performed poorly under drought with low drought tolerance. Grain yield had a very significant positive correlation with effective tiller number, spike length, and thousand-grain weight, particularly under I_3 irrigation. Both PCA and heatmap clustering also confirmed the high genotype × irrigation regime interaction effects, which were optimally expressed by BARI Gom-32 and BARI Gom-25 under I_3. These findings underscore the necessity for optimal, responsive, and flexible water management systems to enhance wheat yield under water-limited conditions, establishing a climate-resilient and agronomically appropriate strategy for augmenting local production in Bangladesh.

Received | August 19, 2025; **Accepted** | February 11, 2026; **Published** | April 03, 2026
***Correspondence** | Mahadi Hasan Monshi, Department of Economics, University of Chittagong, Chittagong-4331, Bangladesh; **Email:** monshimh.cu.de@gmail.com
Citation | Mouri, M.H., M.H. Monshi, R. Tabassum, B.G. Adu, H. Mehraj, M.S. Hossain, J. Hassan, A.K. Hasan and F.I. Monshi. 2026. Strategic irrigation management enhances growth, phenological development, and grain yield in bread wheat (*Triticum aestivum* L.). *Sarhad Journal of Agriculture,* 42(2): 584-600.
DOI | https://dx.doi.org/10.17582/journal.sja/2026/42.2.584.600
Keywords | Bread wheat, Growth, Phenological development, Productivity, Strategic irrigation, and Yield

Introduction

After rice, bread wheat (*Triticum aestivum* L.) is the second most vital cereal crop in Bangladesh, significantly contributing to the country's food supply to satisfy consumer demand and bolster food security (Ahmed *et al*., 2025). Wheat production in Bangladesh peaked in the early 2000s and has since declined due to increasing challenges from erratic weather patterns, heightened water scarcity, and variable climatic conditions, resulting in import dependency (Figure 1). During the past decade, Bangladesh has experienced a pronounced escalation in import volumes, culminating in 6.9 million metric tons in 2024. This quantity, financed by the Government of Bangladesh, corresponded to an expenditure of approximately 2 billion USD (FAO, 2025). Although Bangladesh's winter season (Rabi) offers ideal agroclimatic conditions for its production, the country still depends significantly on wheat imports because of a lack of domestic production for several reasons, including genotypes, soil conditions, and environmental factors, especially irrigation and sowing time (Islam *et al*., 2019; Rahman *et al*., 2021). Therefore, there is an urgent necessity to enhance domestic wheat output by employing current wheat genetic resources and implementing appropriate agronomic practices to reduce import dependency.

Soil moisture levels at critical growth stages have been reported to be highly sensitive to phenological development in wheat, particularly at heading, anthesis, and maturity time (Ihsan *et al*., 2016, Pantha *et al*., 2024). Water stress both in vegetative and reproductive stages, especially at tillering, booting, flowering, or grain-filling periods, can lead to inevitable yield losses owing to decreased grain number, shriveled kernels, and poor development of spikes (Ali *et al*., 2022; Nyaupane *et al*., 2024). The fast and sporadic reduction in groundwater levels, winter precipitation, and increasing competition from alternative crops can obstruct the water supply throughout the wheat-growing season (Mojid, 2019). Consequently, optimal irrigation systems for wheat cultivation are crucial for realizing potential yields (Islam *et al*., 2019; Rahman *et al*., 2024). Over its complete cultivation cycle, wheat requires an estimated 350-450 mm of water, which is aptly distributed among critical phenological stages such as crown root initiation, tillering, flowering, and grain filling (Ahmad and Kumar, 2015; Meena *et al*., 2019). However, vegetative growth and reproductive development of wheat are severely hampered by several components, like timing, frequency, and the amount of watering (Si *et al*., 2023; Zhao *et al*., 2024; Wang *et al*., 2025). Because both excessive or insufficient irrigation can hamper a plant's usual growth and development, as well as waste valuable resources, which encourages the plant to be vulnerable to diseases, namely leaf rust and root rot (Lidwell-Durnin & Lapthorn, 2020; Yan *et al*., 2024). Therefore, it is important to understand how the wheat plant responds to diverse irrigation for developing site-specific water management techniques in changing climatic conditions.

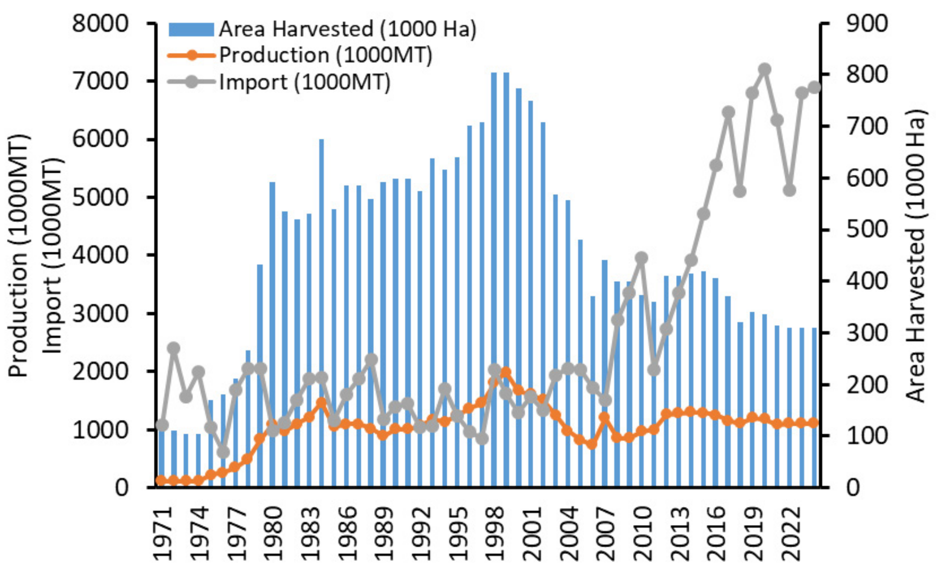

Figure 1: *Annual trends in wheat production and import (both in 1,000 metric tons) and area harvested (in 1,000 hectares) in Bangladesh from 1971 to 2024. (Source: FAOSTAT database): analyzed by the authors.*

Many studies have reported that wheat productivity severely depends on the frequency and timing of irrigations. For instance, Rahman *et al.* (2024) found that three distinct irrigations at the CRI, heading, and grain filling stages ensure proper vegetative growth and development in Bangladesh's climatic conditions. On the other hand, wheat production can be reduced by up to 30% when low irrigation is combined with sensitive growth and developmental stages (Islam *et al*., 2019; Cebi *et al*,. 2023; Wang *et al*., 2024). These results are consistent with studies conducted in other South Asian countries that demonstrated that water scarcity at different critical growth stages can reduce the grain yield (Baloch *et al*., 2014; Anjum *et al*., 2021; You *et al*., 2022; Mobeen *et al*., 2025). The IPCC (2019) stated that regulating irrigation systems can be adaptive to environmental conditions and genotype can reduce groundwater depletion. Additionally, study aimed at discovering water-efficient wheat cultivars has been undertaken using various bread wheat genotypes in Bangladesh (Acharjee & Shariot-Ullah, 2021; Ahmed *et al*., 2023). However, genotype-specific irrigation needs throughout crucial growth phases remain little investigated, especially across the many edaphic and climatic conditions of the nation.

Recent studies in South Asia have highlighted the benefits of precision irrigation techniques, including deficit irrigation and alternate furrow irrigation, in intensifying water productivity without losing grain yield (Sarker *et al*., 2020; Mobeen *et al*., 2025). Little but growing evidence from Bangladesh recommends that adaptive irrigation systems in different agro-ecological climatic zones can extensively promote wheat productivity (Islam and Nursey-Bray, 2017; Hasan *et al*., 2019). Nevertheless, few location-specific factual studies have assessed how strategic irrigation schedules influence the growth, phenology, harvest index, accumulation of biomass, and ultimately grain yield (Islam *et al*., 2019; Rahman *et al*., 2024). Moreover, wheat cultivation has expanded expeditiously in the non-traditional areas of Bangladesh because of the lower profitability of Boro rice cultivation and increased demand for diversified cereal options (Islam and Nursey-Bray, 2017; Mian and Begum, 2020). Divergent soil textures, water-retention capacities, and microclimatic factors are frequently found in these regions, in regarding how the crop responds to irrigation (Hossain and Teixeira da Silva, 2013; Monshi and Malek, 2013; Tabassum *et al*., 2015; Yesmin *et al*., 2022). So, it is essential to assess wheat performance under various irrigation regimes in different environments to produce context-specific insights and policy suggestions.

The present study aims to fill this knowledge gap by addressing the impact of distinct irrigation schedules on the agronomical growth patterns, phenological development, and yield attributes of wheat genotypes cultivated under field conditions in Mymensingh, Bangladesh. Regarding this, we evaluated 7 wheat cultivars in four different irrigation regimes to find out how plants behave under different irrigation schedules, after subsequent evaluation of growth, phenology, and yield traits. Specifically, identifying the most crucial stages of irrigation that impact yield, and suggesting useful advice for the best irrigation practices that wheat farmers can implement in diverse agro-ecological zones. The findings help to inform policymakers and extension officers about the irrigation timing for wheat, guiding farmers to optimize water use for strengthening wheat productivity in a water-constrained environment.

Materials and Method

Experimental site

The experiment was performed at a farmer's field in Muktagacha, Mymensingh, Bangladesh, from November 2024 to March 2025 to assess the morphological, phenological, and yield performance of seven selected wheat genotypes at four distinct irrigation conditions. Geographically, the experimental site (24°25"N latitude and 90°50"E longitude) is situated in the northwest part of Mymensingh district in Bangladesh. The experimental area exhibits a subtropical climate, characterized by elevated temperatures and substantial rainfall during the kharif season (April to September) and limited rainfall coupled with moderately low temperatures and immense light intensity during the rabi season (October to March) (Figure 2). The studied location comprised silty clay loams with substantial water-retention capacity and nutrient-rich, non-calcareous gray alluvial floodplain soil, efficiently drained by the Brahmaputra River and its tributaries (Sheel *et al*., 2016). Ratul *et al*. (2021) and Tabassum *et al*. (2023) previously provided valuable information about the studied area where the soil pH ranged from 5.5 to 6.5, with a substantial organic matter content viz. total nitrogen at 0.15%, available phosphorus at 3.25 ppm, available sulfur at 4.48 ppm, and exchangeable potassium at 0.12 ppm.

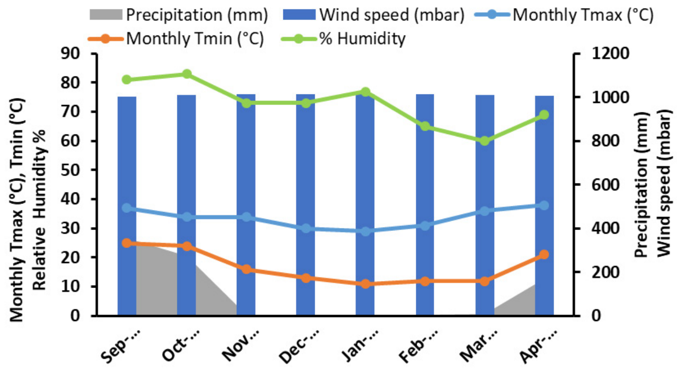

Figure 2: *Monthly climatic variables include average monthly high and low temperatures (°C), precipitation (mm), relative humidity (%), and wind speed (mbar) recorded during the experimental period from September 2024 to April 2025 under a subtropical climate.*

Plant materials

Seven wheat varieties (Protiva, BARI Gom-19, BARI Gom-20, BARI Gom-22, BARI Gom-25, BARI Gom-30, and BARI Gom-32) were used in the present study. Among them, six namely BARI Gom-19, BARI Gom-20, BARI Gom-22, BARI Gom-25, BARI Gom-30, and BARI Gom-32 were collected from the Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh while the Protiva variety was collected from the Bangladesh Wheat and Maize Research Institute (BWMRI), Dinajpur, Bangladesh.

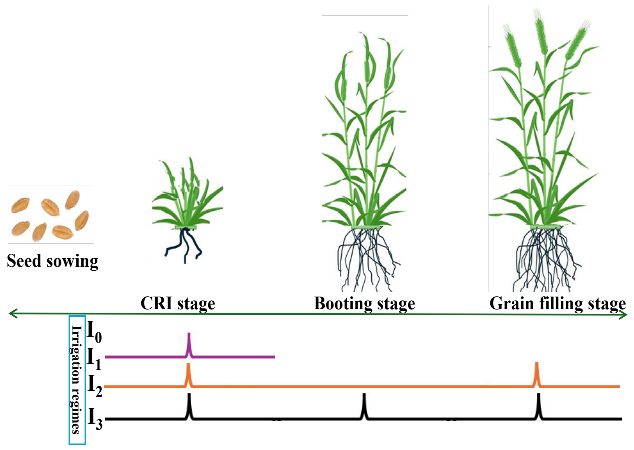

Figure 3: *Schematic representation of irrigation regimes at different stages of phenological growth and development of wheat. I_0 = No irrigation throughout the growing season, I_1 = One irrigation at CRI stage, I_2= Two irrigations at CRI and grain filling stages, I_3= Three irrigations at CRI, booting and grain filling stages.*

Experimental design

The experiment employed a split-plot design with three replications to evaluate the effect of wheat genotypes on their morphological, phenological, and yield-related traits under different irrigation levels. We designed the present experiment as two factors: Factor A (variety) and Factor B (irrigation). Factor A consisted of seven wheat varieties: V_1 = Protiva, V_2 = BARI Gom-19, V_3 = BARI Gom-20, V_4 = BARI Gom-22, V_5 = BARI Gom-25, V_6 = BARI Gom-30, and V_7 = BARI Gom-32. Conversely, four irrigation levels were included in Factor B during the growth period: I_0 = no irrigation, I_1 = one irrigation at the crown root initiation (CRI) stage, I_2 = two irrigations at the CRI and grain filling stages, and I_3 = three irrigations at the CRI, booting, and grain filling phases (Figure 3).

The main plots were assigned irrigation treatments, whereas the sub-plots were randomly allocated wheat genotypes, resulting in twenty-eight treatment combinations (7 genotypes × 4 irrigation levels) assessed across eighty-four plot units. Each plot measured 2.5 m × 2.0 m (5.0 m^2), with a spacing of 20 cm between rows and 5 cm between plants. To keep plots from interfering with each other, there was a 1.0 m space between major plots, a 0.6 m space between sub-plots, and a 0.5 m space between replications were maintained.

Data collection

The agronomic and yield-related trait performance for several wheat varieties was recorded under different irrigation conditions.

Plant height (cm)

Ten randomly selected plants per plot were measured for plant height (in cm) from the base to the top of the tallest spikelet, and an average was measured.

Number of effective tiller hill^{-1}

Tillers with a spike that produced grain were considered as an effective tiller. Ten hills were chosen at random for each plot, and the quantity of productive tillers on each hill was noted. Number of effective tiller hill^{-1} was calculated by using the formula outlined by Gomez and Gomez (1984) as follows:

$$\text{Number of effective tiller hill}^{-1} = \frac{\textit{Number of productive tillers}}{\text{Number of sampled hills}}$$

Number of non-effective tiller hill^{-1} was calculated utilizing the following formula:

Number of non-effective tiller hill^{-1} = Total tillers hill^{-1} – Effective tillers hill^{-1}

Days to heading:

Days to heading were calculated by counting the number of days from the date of sowing to the date when approximately 50% of the plants in each plot showed visible panicle emergence. The plots were checked every day starting 45 days after planting. The date on which the 50% threshold was met was recorded, and the number of days from the sowing date to this observed date was taken as the days to heading for each plot.

Days to maturity

The number of days to maturity was calculated by counting the number of calendar days from the planting date to the date when approximately 90% of the spikes in each plot had turned golden yellow. This stage was confirmed by manually threshing a sample of spikes to ensure the grains had reached physiological maturity. The date of this confirmed maturity was then subtracted from the planting date to determine the total days to maturity for each plot.

Length of spike (cm)

The spike length of the selected samples was measured, and the average was considered.

Number of filled grains spike^{-1}

Ten spikes were chosen at random from ten distinct plants in each plot to calculate the grain count per spike. The mean grain number spike^{-1} was determined by manually counting the number of grains in each spike and averaging them.

Thousand grain weight (g)

One thousand clean, dry, and undamaged seeds were chosen at random from each plot's collected sample. A precise electronic balance was used to measure the total weight of these seeds.

Grain yield (tha^{-1})

The grains from each unit plot were sun-dried to a consistent moisture content and then carefully weighed using an electronic balance. This weight was then increased by the dry grain weight of the selected sample plants. The total grain yield of each plot was calculated and converted in tons per hectare (tha^{-1}).

Straw yield (tha^{-1})

The complete biomass of straw from each experimental unit, including the plants sampled, was harvested and weighed to calculate the straw yield per plot. The ultimate yield, measured in tons per acre, was determined by sun-drying the harvested straw until it reached a consistent weight.

Biological yield (tha^{-1})

Biological yield was calculated using the following known formulas: Grain yield + straw yield = biological yield (tha^{-1})

Statistical analysis

Treatments variation

RStudio version R.4.3.2 was used to conduct statistical analysis. The study employed a one-way analysis of variance (ANOVA) to assess the significance of treatment effects. The replication, treatment, and error components' mean square values were computed using the "agricolae" program.

Mean performance

The package "agricolae" was used to calculate the mean performance with lettering, and MS-excel was used to design the graph that compares various performances across (a) variety, (b) irrigation schedule, and (c) interaction of variety and irrigation schedule for yield, where SY stands for straw yield and BY for biological yield.

Correlation estimation

Pearson's correlation coefficients among traits were calculated using the "corrplot" package.

PCA and heatmap

A multivariate principal component analysis (PCA) was performed using the "factoextra" and "factoMineR" packages to generate a scree plot and calculate the variance contributions (%). PCA biplots were made using the "ggplot2" and "ggrepel" programs. The "heatmaply" software was used to create the PCA heatmap. The "pheatmap" program was used to build heatmap.

Results

ANOVA of agronomic traits under irrigation regimes

The analysis of variance (ANOVA) provided in Table 1 revealed highly significant impacts of both wheat genotypes and irrigation schedules on 12 major morphological, phenological, and yield parameters. The key traits revealed significant variation from

Table 1: *Analysis of Variances (ANOVA) for 12 agronomic and phenological traits of wheat varieties and irrigation schedule.*

Source of variation	df	PH	ET	NET	DH	DM	LS	NGS	TGW	Yield	SY	BY	HI
	Genotypes												
Replication	2	2.33^{**}	0.19^{***}	0.04^{***}	4.14^{***}	13.37^{***}	0.92^{***}	0.76	15.60^{***}	0.01^{***}	0.01	0.01	1.64
Treatment	6	27.45^{***}	$0.7^{4**}*$	0.16^{***}	$15.5^{6**}*$	46.63^{***}	$9.5^{0**}*$	67.69^{***}	98.49^{***}	2.09^{***}	0.50^{***}	3.36^{***}	73.01^{***}
Error	72	0.46	0.01	0.01	0.31	0.78	0.07	0.47	0.44	0.01	0.02	0.02	1.29
	Irrigation schedule												
Replication	2	2.34^{**}	0.18^{***}	0.05^{***}	4.15^{***}	13.40^{***}	0.91^{***}	0.75	15.55^{***}	0.01^{***}	0.01	0.01	1.65
Treatment	3	59.31^{***}	7.60^{***}	1.85^{***}	35.22^{***}	13.37^{***}	39.34^{***}	63.25^{***}	32.59^{***}	1.34^{***}	0.13^{**}	1.41^{***}	65.65^{***}
Error	72	0.46	0.01	0.01	0.33	0.77	0.07	0.47	0.44	0.01	0.03	0.02	1.29
	Interaction of wheat genotypes and irrigation schedule												
Replication	2	2.33^{*}	0.19^{***}	0.05^{**}	4.12^{***}	13.48^{***}	0.91^{***}	0.75	15.59^{***}	0.01^{***}	0.01	0.01	1.65
Treatment	27	12.69^{***}	1.01^{***}	0.24^{***}	7.37^{***}	11.85^{***}	6.48^{***}	22.07^{***}	25.51^{***}	$0.6^{1**}*$	0.18^{***}	0.96^{***}	26.36^{***}
Error	54	0.62	0.01	0.01	0.31	0.79	0.09	0.45	0.46	0.01	0.02	0.03	1.31

Note: PH=Plant height (cm), ET=Number of effective tiller hill^{-1}, NET=Number of non-effective tiller hill^{-1}, DH=Days to heading, DM=-Days to maturity, LS=Length of spike (cm), NGS=Number of grain spike^{-1}, TGW=Thousand grain weight (g), Yield=Grain yield (tha^{-1}), SY=Straw yield (tha^{-1}), BY=Biological yield (tha^{-1}), HI=Harvest index (%).

Table 2: *Impact of varietal differences and irrigation scheduling on growth, phenology, and yield of different wheat varieties.*

Treatments	PH	ET	NET	DH	DM	LS	NGS	TGW	HI
Genotypes									
V_1	90.94^{d}	5.58^{a}	1.47^{a}	54.39^{f}	102.92^{b}	10.95^{e}	40.37^{d}	44.25^{e}	49.13^{d}
V_2	92.98^{c}	5.49^{b}	1.36^{b}	55.92^{c}	104.25^{a}	11.17^{e}	44.27^{c}	44.71^{e}	48.76^{d}
V_3	94.56^{ab}	5.43^{b}	1.34^{bc}	55.15^{d}	103.05^{b}	11.69^{d}	45.72^{b}	45.41^{d}	49.22^{d}
V_4	94.13^{b}	5.01^{de}	1.31^{cd}	57.65^{a}	104.08^{a}	12.55^{c}	48.01^{a}	44.60^{e}	50.17^{c}
V_5	94.89^{a}	4.98^{e}	1.27^{d}	56.44^{b}	102.58^{b}	12.45^{c}	46.05^{b}	50.04^{b}	53.18^{b}
V_6	94.99^{a}	5.07^{d}	1.15^{e}	55.12^{de}	99.57^{c}	12.98^{b}	46.15^{b}	46.87^{c}	53.89^{ab}
V_7	95.11^{a}	5.30^{c}	1.14^{e}	54.67^{ef}	99.52^{c}	13.25^{a}	45.81^{b}	51.39^{a}	54.38^{a}
$LSD_{(0.05)}$	0.55	0.08	0.04	0.45	0.72	0.22	0.56	0.54	0.93
CV (%)	0.72	1.78	4.06	1.01	0.86	2.25	1.53	1.43	2.22
Irrigation schedule									
I_0	91.70^{d}	4.52^{d}	1.68^{a}	53.93^{d}	101.17^{c}	10.54^{d}	42.80^{d}	45.08^{c}	49.08^{c}
I_1	93.72^{c}	5.06^{c}	1.35^{b}	55.32^{c}	102.27^{a}	11.67^{c}	44.83^{c}	46.58^{b}	50.96^{b}
I_2	94.77^{b}	5.62^{b}	1.14^{c}	56.38^{b}	102.75^{ab}	12.62^{b}	45.88^{b}	47.46^{a}	51.56^{b}
I_3	95.59^{a}	5.87^{a}	0.99^{d}	56.85^{a}	102.96^{a}	13.76^{a}	46.85^{a}	47.90^{a}	53.37^{a}
$LSD_{(0.05)}$	0.42	0.06	0.03	0.34	0.45	0.17	0.42	0.41	0.70
CV (%)	0.73	1.78	4.06	1.01	0.86	2.25	1.53	1.43	2.22

Note: Here, PH=Plant height (cm), ET=Number of effective tiller hill^{-1}, NET=Number of non-effective tiller hill^{-1}, DH=Days to heading, DM=Days to maturity, LS=Length of spike (cm), NGS=Number of grain spike^{-1}, TGW=Thousand grain weight (g), HI=Harvest index (%).

variety treatments (V_1 to V_7) at the 1% significance level, including number of effective tillers hill^{-1} (0.74^{***}), days to heading (15.56^{***}), days to maturity (46.63^{***}), length of spike (9.50^{***}), number of grain spike^{-1} (67.69^{***}), thousand grain weight (98.49^{***}), grain yield (2.09^{***}), and harvest index (73.01^{***}). Similarly, all traits exposed highly significant effects ($p < 0.001$) from irrigation treatments (I_0 to I_3), where the significant variation in plant height (59.31^{***}), number of effective tiller hill^{-1} (7.60^{***}), length of spike (39.34^{***}), number of grain spike^{-1} (63.25^{***}), thousand grain weight (32.59^{***}), grain yield (1.34^{***}), and harvest index (65.65***) indicate that water availability has a dominant effect on morphological, phenological, and yield traits. Furthermore, there is a significant difference among genotype × irrigation interactions of yield traits, including number of grain spike^{-1} (22.07***), thousand grain weight (25.51***), grain yield (0.61***), straw yield (0.18***), biological yield (0.96***), and harvest index (26.36***).

Influence of genotypes and irrigation regimes on wheat performance

The growth, phenological development, and yield-contributing traits of wheat genotypes were greatly influenced by the irrigation schedule and varietal differences, displayed in Table 2. The highest plant height (95.11 cm), length of spike (13.25 cm), thousand grain weight (51.39 g), and harvest index (54.38%) were recorded in BARI Gom-32 (V_7), while Protiva (V_1) revealed low performance across the traits. Yield attributes increased gradually from no irrigation (I_0) to the maximum irrigation level (I_3). Irrigation treatment I_3, produced the highest values in plant height (95.59 cm), number of effective tillers hill^{-1} (5.87), length of spike (13.76 cm), thousand grain weight (47.90 g), and harvest index (53.37%). In contrast, the I_0 treatment led to decreased performance, especially in effective tillers (4.52), spike length (10.54 cm), number of grain spike^{-1} (42.80),

Table 3: *Interaction effect of variety and irrigation scheduling on growth, phenology, and yield of different wheat varieties.*

Interaction	PH	ET	NET	DH	DM	LS	NGS	TGW	HI
V_1I_0	88.70^{l}	4.84^{k}	1.86^{a}	51.88^{n}	101.88^{f-h}	9.35^{q}	38.08^{n}	42.57^{o}	45.25^{q}
V_2I_0	90.73^{k}	4.75^{k}	1.75^{b}	54.67^{k-m}	103.13^{b-g}	9.57^{q}	41.98^{kl}	43.04^{no}	46.07^{pq}
V_3I_0	92.32^{j}	4.69^{kl}	1.73^{b}	53.37^{mn}	101.93^{fg}	10.09^{p}	43.43^{ij}	43.73^{m-o}	46.88^{op}
V_4I_0	91.88^{jk}	4.26^{m}	1.70^{b}	55.37^{f-h}	102.97^{d-g}	10.95^{m-o}	45.71^{e-g}	42.93^{no}	48.29^{mn}
V_5I_0	92.65^{h-j}	4.23^{m}	1.66^{b}	54.17^{j-l}	101.47^{g-i}	10.85^{no}	43.77^{hi}	49.72^{d}	52.18^{ef}
V_6I_0	92.87^{h-j}	4.32^{m}	1.54^{c}	53.00^{mn}	98.45^{k}	11.38^{lm}	43.87^{hi}	45.19^{i-l}	52.37^{ef}
V_7I_0	92.76^{h-j}	4.56^{l}	1.53^{c}	52.48^{n}	98.40^{k}	11.65^{j-l}	42.80^{i-k}	48.36^{e}	52.57^{de}
V_1I_1	90.72^{k}	5.37^{hi}	1.53^{c}	53.18^{lm}	102.98^{d-g}	10.48^{op}	40.12^{m}	44.08^{l-n}	47.53^{no}
V_2I_1	92.75^{h-j}	5.29^{hi}	1.42^{d}	55.97^{g-j}	104.23^{a-e}	10.70^{o}	44.02^{hi}	44.54^{j-m}	48.95^{lm}
V_3I_1	94.33^{fg}	5.23^{ij}	1.40^{de}	54.67^{i-l}	103.03^{d-g}	11.22^{l-n}	45.47^{fg}	45.23^{i-l}	49.26^{kl}
V_4I_1	93.90^{gh}	4.80^{k}	1.37^{de}	56.67^{cd}	104.07^{a-e}	12.08^{i-k}	47.74^{b-d}	44.43^{k-m}	49.70^{i-l}
V_5I_1	94.67^{d-g}	4.77^{k}	1.33^{de}	55.47^{e-h}	102.57^{e-g}	11.98^{jk}	45.80^{e-g}	51.23^{bc}	53.41^{cd}
V_6I_1	94.88^{d-g}	4.86^{k}	1.21^{f}	54.30^{j-l}	99.55^{jk}	12.51^{hi}	45.90^{e-g}	46.69^{fg}	53.81^{c}
V_7I_1	94.77^{d-g}	5.09^{j}	1.20^{f}	53.78^{k-m}	99.50^{jk}	12.78^{gh}	44.83^{gh}	49.87^{d}	54.09^{c}
V_1I_2	91.77^{jk}	5.94^{b-d}	1.32^{e}	54.65^{h-k}	103.46^{a-f}	11.43^{lm}	41.17^{lm}	44.95^{i-m}	49.47^{j-l}
V_2I_2	93.80^{g-i}	5.85^{d}	1.21^{f}	57.43^{c-f}	104.72^{a-c}	11.64^{kl}	45.07^{gh}	45.42^{h-k}	49.96^{i-k}
V_3I_2	95.38^{b-f}	5.79^{de}	1.19^{f}	56.13^{f-h}	103.51^{a-f}	12.16^{ij}	46.52^{d-f}	46.11^{g-i}	50.48^{hi}
V_4I_2	94.95^{c-g}	5.36^{hi}	1.16^{fg}	58.13^{ab}	104.55^{a-d}	13.02^{e-g}	48.79^{ab}	45.31^{h-l}	51.21^{gh}
V_5I_2	95.72^{a-e}	5.33^{hi}	1.12^{f-h}	56.93^{cd}	103.05^{c-g}	12.92^{f-h}	46.85^{c-e}	52.10^{ab}	51.79^{e-g}
V_6I_2	95.93^{a-d}	5.42^{gh}	1.00^{i}	55.77^{f-i}	100.03^{i-k}	13.45^{de}	46.95^{c-e}	47.57^{ef}	53.98^{c}
V_7I_2	95.82^{a-e}	5.66^{ef}	0.99^{i}	55.25^{g-j}	99.98^{i-k}	13.73^{cd}	45.88^{e-g}	50.75^{cd}	54.03^{c}
V_1I_3	92.59^{ij}	6.18^{a}	1.17^{f}	55.05^{g-j}	103.66^{a-e}	12.57^{g-i}	42.13^{j-l}	45.40^{h-k}	54.30^{c}
V_2I_3	94.62^{e-g}	6.10^{ab}	1.06^{g-i}	57.83^{c-e}	104.92^{a}	12.78^{gh}	46.03^{e-g}	45.86^{g-i}	50.04^{i-k}
V_3I_3	96.21^{a-c}	6.03^{a-c}	1.04^{hi}	56.53^{d-g}	103.71^{a-e}	13.31^{d-f}	47.48^{cd}	46.55^{f-h}	50.25^{ij}
V_4I_3	95.77^{a-e}	5.61^{f}	1.01^{i}	58.53^{a}	104.75^{ab}	14.16^{bc}	46.85^{c-e}	45.76^{g-j}	51.47^{fg}
V_5I_3	96.54^{ab}	5.58^{fg}	0.97^{i}	57.33^{bc}	103.25^{a-f}	14.06^{c}	47.82^{b-d}	51.19^{bc}	55.33^{b}
V_6I_3	96.76^{a}	5.67^{ef}	0.85^{j}	56.17^{d-g}	100.23^{h-j}	14.59^{ab}	47.92^{bc}	48.01^{e}	55.42^{b}
V_7I_3	96.65^{ab}	5.91^{cd}	0.84^{j}	55.65^{f-i}	100.18^{ij}	14.87^{a}	49.76^{a}	52.55^{a}	56.83^{a}
$LSD_{(0.05)}$	1.28	0.17	0.09	1.05	1.67	0.51	1.31	1.26	0.91
CV (%)	0.84	2.05	4.69	1.15	0.99	2.59	1.77	1.65	1.08

Note: *Here, PH=Plant height (cm), ET=Number of effective tiller hill^{-1}, NET=Number of non-effective tiller hill^{-1}, DH=Days to heading, DM=Days to maturity, LS=Length of spike (cm), NGS=Number of grain spike^{-1}, TGW=Thousand grain weight (g), HI=Harvest index (%)*

thousand-grain weight (45.08 g), and harvest index (49.08%). Additionally, phenological traits differed significantly between varieties and irrigation levels. BARI Gom-22 (V_4) showed the longest durations to heading (57.65 days) and maturity (104.08 days), whereas V_6 (BARI Gom-30) and V_7 (BARI Gom-32) exposed the shortest durations to heading (54.39 days) and maturity (99.52 days), respectively. Finally, significant genotype × irrigation responses were further confirmed by the interaction effects (Table 3), where maximum plant heights were shown by V_6I_3 (96.76 cm), while the lowest were found in V_1I_0 (88.70 cm). Non-effective tillers were reduced in V_7I_3 (0.84), while effective tillers peaked in V_1I_3 (6.18). The earliest heading and maturity periods under stress were displayed by V_1I_0 (51.88 days) and V_6I_0 (98.45 days), while the longest values were uncovered by V_4I_3 (58.53 days) and V_2I_3 (104.92 days). The genotype × irrigation also improved the components of grain yield at full irrigation level (I_3), with the longest length of spike (14.87 cm), the most grains spike^{-1} (49.76), the thousand grain weight (52.55 g), and the harvest index (56.83%) for V_7I_3.

Differences in yield traits

The production of wheat grain yield, straw yield, and biological yield are influenced by variety, irrigation schedule, and their interactions, illustrated in Figure 4, where variety V_1 (Protiva) and V_2 (BARI Gom-19) exhibited diminished productivity, suggesting restricted adaptability and inefficient resource utilization, whereas V_7 (BARI Gom-32) and V_6 (BARI Gom-30) consistently surpassed the other genotypes, achieving the highest grain yields (4.66 tha^{-1} and 4.42 tha^{-1}, respectively), reflecting significant stress tolerance and robust genetic potential (Figure 4a). Similarly, the impact of irrigation was equally profound, with a gradient of improvement observed from zero irrigation (I_0) to the fully irrigated regime (I_3). Among various irrigation conditions, I_3 demonstrated a notable increase in grain yield (4.34 tha^{-1}), straw yield (3.17 tha^{-1}), and biological yield (7.44 tha^{-1}), all of which highlighted the importance of water availability at crucial points (Figure 4b). Among these variety and irrigation interactions, the $V_7 \times I_3$ combination highlighting the maximum

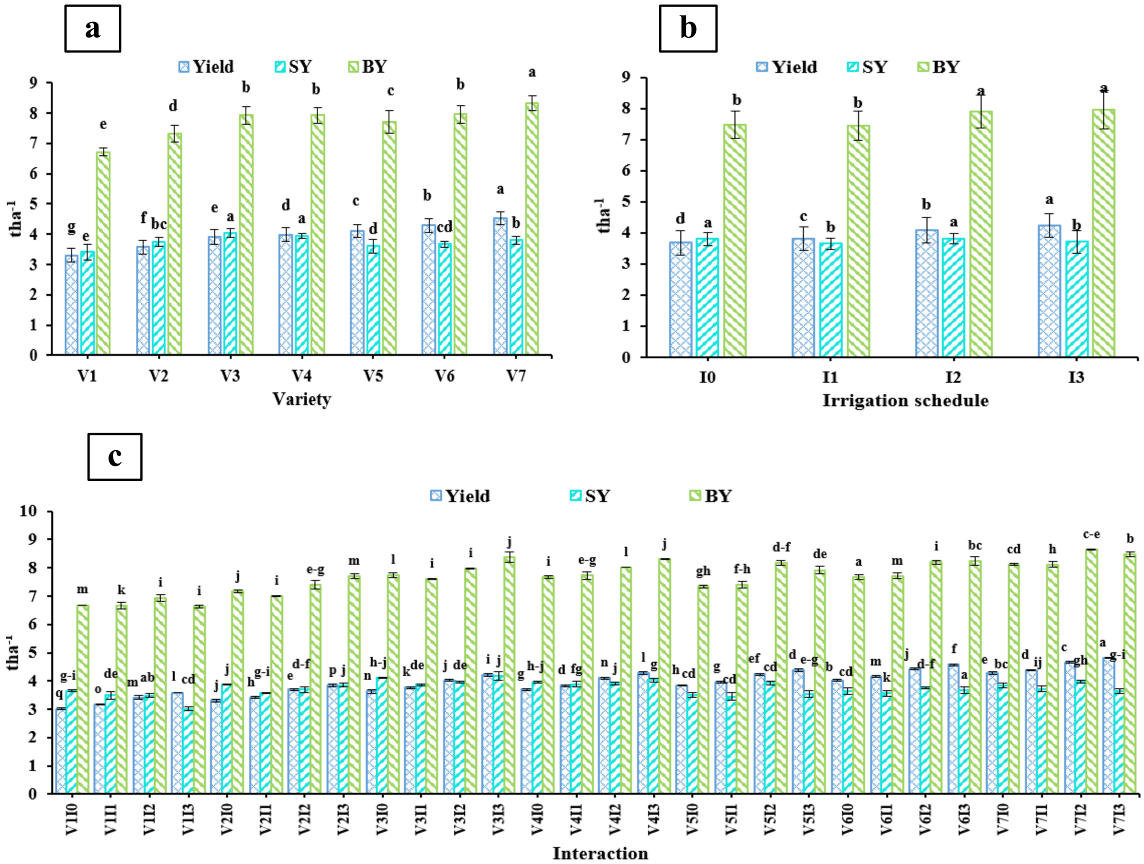

Figure 4: *Comparison of different performances across (a) Variety, (b) Irrigation schedule and (c) Interaction of wheat variety and irrigation schedule for yield (grain yield, tha^{-1}), SY=Straw yield (tha^{-1}), BY=Biological yield (tha^{-1}). Mean values are presented with standard deviation, and significant differences are indicated based on Duncan's multiple range test at P<0.05.*

grain yield (4.82 tha^{-1}), straw yield (3.65 tha^{-1}), and biological yield (8.47 tha^{-1}), closely followed by $V_6 \times I_3$ (Figure 4c).

Pearson correlation analysis

Twelve important agronomic traits were analyzed using Pearson correlation under three distinct conditions: (a) variety; (b) irrigation schedules; and (c) the interaction between wheat variety and irrigation schedule. Across the varieties, the most important trait, yield, was positively correlated with the number of effective tiller $hills^{-1}$ (0.98^{***}), length of spike (0.99^{***}), number of grain $spike^{-1}$ (0.98^{***}), and thousand grain weight (0.99^{***}), straw yield (0.98^{***}), biological yield (1.00^{***}) and harvest index (1.00^{***}). but negatively connected with the number of non-effective tiller $hills^{-1}$ (-0.96^{***}) Figure 5a. In irrigation schedule, yield was strongly influenced by the thousand-grain weight (0.98^{*}), number of grain $spike^{-1}$ (0.98^{*}), and length of spike (0.98^{*}) Figure 5b. Three irrigations (I_3) strengthened these relationships, while no irrigation (I_0) weakened them. Significantly, correlations between yield and important traits were strengthened by irrigation during critical stages (CRI, booting, and grain filling), highlighting the importance of strategic water management. Finally, interaction of variety and irrigation provided stronger correlation compare to variety and irrigation (Figure 5c),

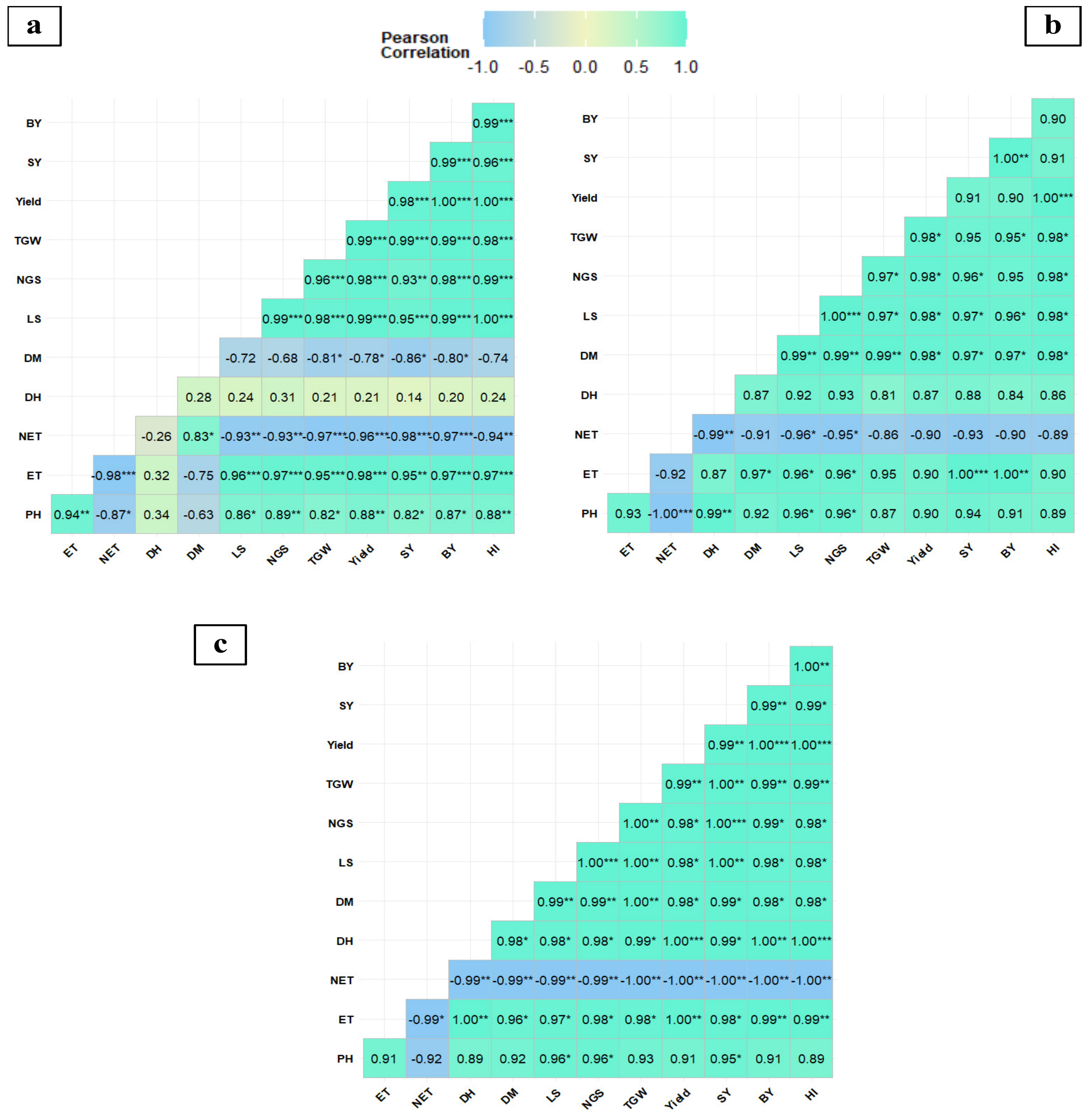

Figure 5: *Correlation among 12 agronomic and phenological traits under (a) variety, (b) irrigation schedule, and (c) interaction of wheat varieties and irrigation schedule. The light blue color indicates a negative correlation, while the light green color indicates a positive correlation. The color intensity increases with its significance level. Here, PH=Plant height (cm), ET=Number of effective tillers $hill^{-1}$, NET=Number of non-effective tiller $hill^{-1}$, DH=Days to heading, DM=Days to maturity, LS=Length of spike (cm), NGS=Number of grain $spike^{-1}$, TGW=Thousand grain weight (g), Yield (tha^{-1}), SY=Straw yield (tha^{-1}), BY=Biological yield (tha^{-1}), HI=Harvest index (%).*

where yield showed strong positive correlations with effective tillers (1.00***), spike length (0.98*), number of grain spike^{-1} (0.98*), thousand grain weight (0.99**), straw yield (0.99***), biological yield (1.00***), and harvest index (1.00***). This pattern intensified with nearly perfect correlation across all major yield determinants. These findings indicate how optimal irrigation schedule and higher genetic potential combine to improve traits that contribute to wheat production.

PCA analysis

Principal Component Analysis (PCA) was utilized to perceive the multivariate interactions between wheat genotypes and irrigation regimes across the assessed traits (Figure 6). The first two principal components (PC1 and PC2) together explained 76.6% of the combined variation, with PC1 accounting for 57.7% and PC2 for 19.2% (Figure 6a). The results of the interactions between irrigation and varieties were displayed in the PCA biplot (Figure 6b). In first quadrant, days to heading, number of effective tillers hill^{-1}, and number of grain spike^{-1} plotted positive values in both PC1 and PC2 with the longer distance for V_4I_3, indicating BARI Gom-22 provided suitable values for these traits at irrigation level I_3. In the second quadrant, V_1I_1 showed a longer distance for the trait days to maturity, indicating that the variety Protiva exhibited the highest days to maturity at I_1 irrigation level. Positioned in the third quadrant, V_1I_0 provided longer distance for number of non-effective tiller hill^{-1}. Finally, in forth quadrant, V_7I_3 exhibited longer distance with near traits length of spike, thousand grain weight, yield, biological yield, and harvest index, underscoring that BARI Gom-32 is suitable for these important traits at irrigation level I_3. The principal component scores (Figure 6c) supported this pattern, with the highest values corresponding to

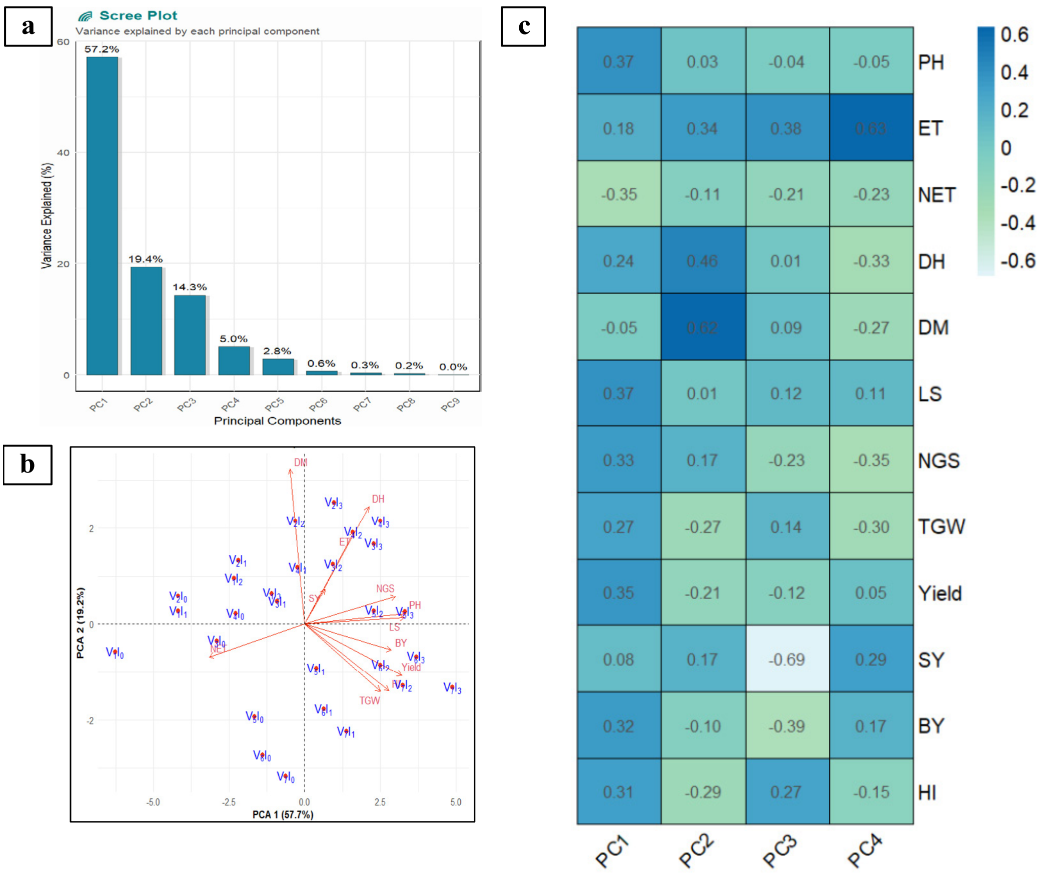

Figure 6: *The scree plot (a) biplot (b) of wheat varieties and irrigation schedule interaction for PC1 and PC2. The arrows in biplot show the contribution (magnitude and direction) of the 12 traits in PC1 and PC2. (c) Principal component analysis (PCA) and its component value for 12 agronomic and phenological traits of wheat varieties and irrigation schedule interaction. Note: Here, PH=Plant height (cm), ET=Number of effective tiller hill^{-1}, NET=Number of non-effective tiller hill^{-1}, DH=Days to heading, DM=Days to maturity, LS=Length of spike (cm), NGS=Number of grain spike^{-1}, TGW=Thousand grain weight (g), Yield (tha^{-1}), SY=Straw yield (tha^{-1}), BY=Biological yield (tha^{-1}), HI=Harvest index (%).*

the I_3 regime when combined with high-performing varieties. Grain yield (0.35), biological yield (0.32), thousand grain weight (0.27), length of spike (0.37), harvest index (0.31), and number of grain spike^{-1} (0.33) were contributed positively to PC1.

Heatmap analysis

Agronomic, phenological, and yield traits provided clear varietal diversity triggered by irrigation, according to the heatmap analysis (Figure 7). The highest values for length of spike, thousand-grain weight, and number of grain spike^{-1}, grain yield, biological yield, and harvest index were consistently found in V_7I_3. This result indicated that under I_3 irrigation conditions, V_7 (BARI Gom-32) performed better than the other varieties. Similarly, V_5 (BARI Gom-25) had the most effective tillers hill^{-1} under I_3, highlighting the significance of irrigation at crucial points. On the other hand, V_1I_0 exhibited the lowest values for length of spike, thousand grain weight, and number of grain spike^{-1}, grain yield, biological yield, and harvest index. This finding implied that V_1 (Protiva) produced the lowest yield-related traits compared to other varieties at irrigation level I_0. Overall, the heat map demonstrated that water stress significantly decreased the growth and yield components, but the optimum irrigation schedule combined with high-performing varieties increased productivity.

Discussion

This study reveals that the use of precision-based irrigation control systems substantially impacts the morphological, phenological, and yield characteristics of wheat, particularly when adapted to genotype-specific responses to various agroecological regions in Bangladesh. The significant influences of irrigation schedules and genotypic variation on all measured parameters ($p < 0.001$) illustrate the significance of genotype × irrigation interactions in enhancing wheat yield.

The ANOVA revealed significant variances ($p < 0.001$)

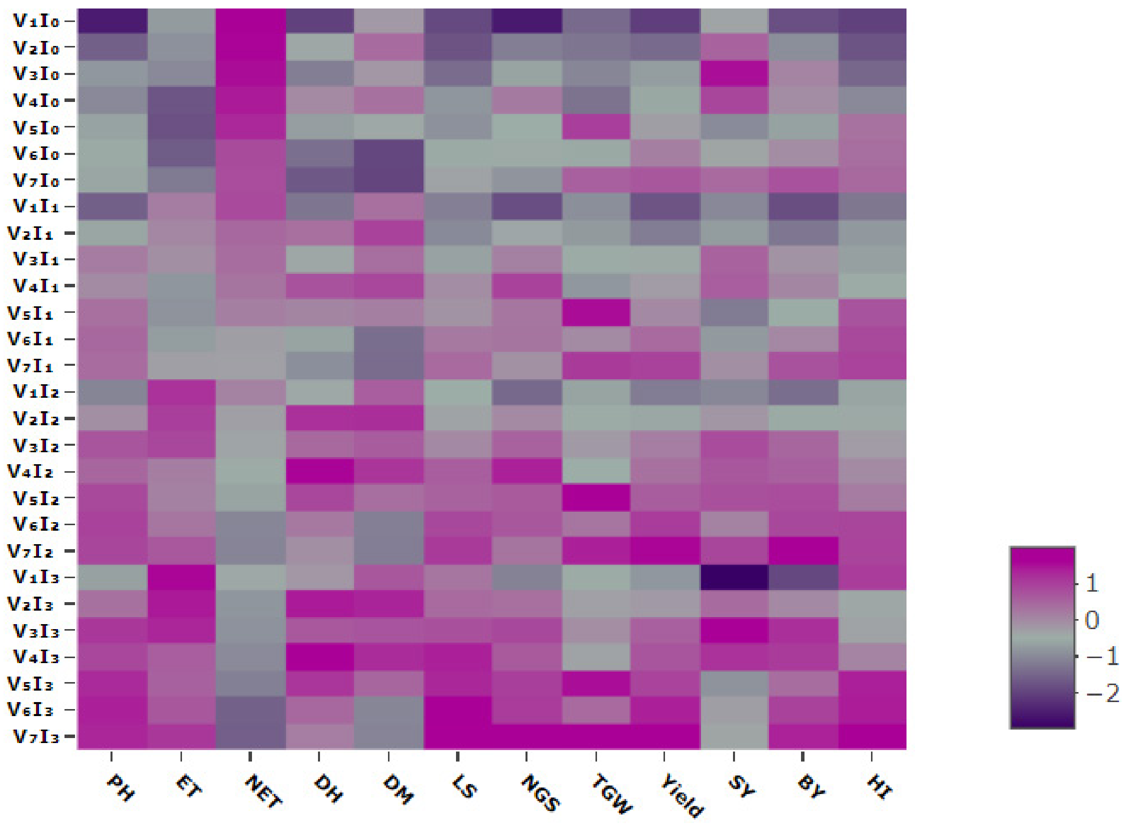

Figure 7: *Heat map analysis outlining the differential responses of agronomic and phenological traits of different wheat varieties and irrigation scheduling interaction. Deep violet indicated lower value and magenta indicated higher value within the interaction of wheat varieties and irrigation scheduling. Note: Here, PH=Plant height (cm), ET=Number of effective tiller hill^{-1}, NET=Number of non-effective tiller hill^{-1}, DH=Days to heading, DM=Days to maturity, LS=Length of spike (cm), NGS=Number of grain spike^{-1}, TGW=Thousand grain weight (g), Yield (tha^{-1}), SY=Straw yield (tha^{-1}), BY=Biological yield (tha^{-1}), HI=Harvest index (%).*

Links Researchers

across all evaluated traits, indicating that both irrigation and genotype exert considerable effects on twelve traits. These findings corroborate previous studies highlighting the essential influence of genetic composition and water availability on wheat performance (Mutanda *et al*., 2025; Zhao *et al*., 2025). Irrigation at three distinct growth stages (I_3), specifically CRI, booting, and grain filling, markedly improves several measures, including plant height, effective tillers hill^{-1}, thousand grain weight, and spike length, hence influencing grain output. The highest growth sensitivity in the critical stages of wheat, such as CRI, heading, and grain filling, was also observed in the previous report by Monteleone *et al*. (2023); Mu *et al*. (2021). The enhanced performance under I_3 corroborates the findings of Liu *et al*. (2024), who found that irrigation in a timely manner profoundly enhances biomass distribution and harvest index. The observed phenological variation among the tested wheat genotypes under differential irrigation levels reflects fundamental genetic regulatory mechanisms. BARI Gom-32 (V_7) is an early maturing cultivar, while BARI Gom-22 (V_4) requires extended growth period. The phenological variety between BARI Gom-32 (V_7) and BARI Gom-22 (V_4) reflects agronomically important traits that can be effectively employed in adaptable climate-resilient plant breeding amidst evolving climatic conditions (Ihsan *et al*., 2016). This temporal flexibility enables crops to evade critical stress windows caused by increasingly shorter winters and late-season aridity. Protiva (V_1) and other genotypes exhibit enhanced heading and maturity under extreme moisture conditions (I_0), underscoring the presence of drought resistance mechanisms. However, the absence of correlation with increased yield aligns with Sewore *et al*. (2024) and recommends no connection between phenological escape and yield potential. On the other hand, delayed phenology under higher irrigation levels (I_3) suggests that more water availability extends vegetative growth and delays senescence. This promotes uninterrupted nutrient absorption and biomass accumulation across the grain-filling period, resulting in increased grain weight and improved yield stability (Du *et al*., 2022; Monteleone *et al*., 2023; Zhuang *et al*., 2024). These findings are aligned with Liu *et al*. (2024), who provided the valuable insight of keeping sufficient water content during the grain-filling stage enhances sink strength, which reinforce the significance of combining phenological adaptability, water-use precision, and yield stability in breeding programs to create suitable wheat cultivars to encounter future challenges of ever-changing climatic conditions (Mu *et al*., 2021).

The notable genotype × irrigation correlations for yield-related parameters (e.g., grain spike^{-1}, thousand grain weight, biological yield, and harvest index) affirm that optimal irrigation is inadequate without genetic compatibility. BARI Gom-32 (V_7) consistently surpassed other genotypes across all irrigation regimes, particularly under I_3, in metrics such as thousand-grain weight (52.55), length of spike (14.87 cm), yield (4.82 tha-1) and harvest index (56.83%). Such superior performance is probably an outcome of their genetic potential for resource-use efficiency and better physiological adaptation, consistent with reports by Bapela *et al*. (2022), who observed genotypic difference under water use efficiency in high-yielding wheat cultivars in South Asia. Protiva's (V_1) poor performance under drought (I_0) is another reflection of the vulnerability of poorly adapted cultivars to water stress.

Pearson correlation showed strong and positive correlations of grain yield with most influential physiological and morphological traits. These include the number of effective tillers hill^{-1} ($r = 1.00^{***}$), length of spike ($r = 0.98^{***}$), and thousand-grain weight ($r = 0.99^{***}$). These results underscore how these attributes function collectively to improve yield under full irrigation level (I_3), harmonious with the result of Liu *et al*. (2024), who identified that improved sink-source regulation is crucial for expanding wheat yield. The consistent associations under diverse irrigation at different stages propose a balanced response to water supply that helps with prominent growth, biomass accumulation, and yield improvement. Additionally, the negative relation between yield and the number of non-effective tillers hill^{-1} shows how unproductive biomass distribution can reduce total grain yield. This is likely due to increased spikelet sterility and floret abortion under suboptimal conditions, as noted by Rahman *et al*. (2024). In these results, Zhuang *et al*. (2024) reported the importance of spike-related traits and grain weight for predicting wheat yield, particularly with optimal irrigation conditions in different growth stages. Together, these results imply that improving watering practices and increasing the use of productive tillers can profoundly enhance the potential of wheat yield.

The Principal Component Analysis (PCA) provides an extensive perception of the intricate interactions among the measured genotypes and irrigation level which influence wheat yield production through numerous mechanisms. The first two principal components (PC1 and PC2) simultaneously described 76.6 percent of the total variation confirming PCA's strength in simplifying complex trait interdependences. With adequate water supply, the full irrigation regime (I_3), BARI Gom-32 and BARI Gom-22 exhibited significant correlations with key yield-attributing characteristics, as they were positioned furthest along the positive axes of PC1 and PC2, respectively. BARI Gom-32 exhibited superior adaptation to optimal moisture availability, correlating with thousand-grain weight, spike length, grain production, biological yield, and harvest index (Anjum *et al*., 2021; Islam *et al*., 2019; Wang *et al*., 2025). These traits are key identifiers of source-sink efficiency, known to improve with enough irrigation facilities, enhancing efficient grain filling and biomass allocation (Ahmed *et al*., 2023; Çebi *et al*., 2023). Conversely, Protiva's (V_1I_0) placed in the negative quadrant of the biplot, along with traits like the number of non-effective tillers hill^{-1}, suggests an inappropriate response to water stress. This is likely caused by reduced translocation of photosynthate, higher floret abortion, and development of impaired spikelet (Si *et al*., 2023; Wang *et al*, 2024; Zhao *et al*., 2024). These findings are consistent with previous research on wheat physiology under drought stress, emphasizing the detrimental impacts of water shortage on source (photosynthesis and biomass) and sink (grain) growth (Liu *et al*., 2024; Yan *et al*., 2024). In addition, spike length, spike grain number, thousand-grain weight, and yield-related indices had strong positive correlations with each other, particularly under I_3, according to the directed loading vectors. High-performing genotypes harness water availability to boost yield components synergistically, an expression of coordinated physiological reaction (Monteleone *et al*., 2023; Zhuang *et al*., 2024). Finally, the multivariate approach of PCA confirmed the advantage of specific genotype and irrigation interactions (specifically V_7I_3 and V_5I_3) and demonstrated the effectiveness of PCA analysis in trait-based selection techniques in selecting high-yielding, climate-stable wheat genotypes (Rahman *et al*., 2024; Wang *et al*., 2025).

The heat map analysis helps in interpreting the differential adaptation of wheat genotypes to different water regimes by providing an extensive description of genotype × irrigation interactions across several agronomic, phenological, and yield traits. BARI Gom-32 (V_7) consistently performed well in important yield components such as length of spike (LS), thousand grain weight (TGW), number of grains spike^{-1} (NGS), grain yield (Yield), biological yield (BY), and harvest index (HI) under the ideal irrigation schedule (I_3), highlighting its agronomic stability and physiological robustness under well-watered conditions (Islam *et al*., 2019; Rahman *et al*., 2021; Wang *et al*., 2024). Similarly, BARI Gom-25 (V_5) demonstrated a marked increase in effective tillers hill^{-1} (ET), confirming the importance of timely irrigation during sensitive phenophases like booting, grain filling, and CRI, which are essential for improving assimilate allocation and tiller fertility (Bapela *et al*., 2022; Zhao *et al*., 2025). Concurrently, Protiva (V_1) exhibited the lowest performance among the studied genotypes under the water stress condition (I_0). This occurred because insufficient water stress encourages reduced transport of assimilates and excessive floret abortion through reduction of photosynthetic activity, sink capacity, and spike length elongation (Liu *et al*., 2024; Mutanda *et al*., 2025). These findings corroborate previous reports that irrigation-induced morphological and physiological trait control directly governs wheat yield development and resource-use efficiency (Baloch *et al*., 2014; Islam *et al*., 2019; Çebi *et al*., 2023). Overall, well-irrigation management along with high-yielding genotypes like BARI Gom-32 and BARI Gom-25 improves the stability against environmental variations and maximizes production potential in irrigated and stressed environments. Recent achievements in breeding and agronomic research have highlighted the essential role of the synergy between genotype and environment in developing climate-adaptive wheat genotypes (Ihsan *et al*., 2016; Sen *et al*., 2017; Mu *et al*., 2021; Monteleone *et al*., 2023).

Recent climate change settings in South Asian agriculture impacted the wheat cultivation and its production trends (Mobeen *et al*., 2025; Sarker *et al*., 2020), as documented by Rehman *et al*. (2024), revealing the urgent requirement for adopting fruitful strategies in wheat farming in Bangladesh. This study underscores the necessity of implementing climate-resilient agriculture practices that incorporate genotypic selection with precision irrigation approaches. The favorable outcomes of BARI Gom-

32 and BARI Gom-25 at appropriate soil moisture levels indicated significant yield advantages from the promotion of genetically robust and high-yielding wheat genotypes. In stage-specific irrigation, particularly during the critical stages of CRI, booting, and grain filling, these varieties can substantially improve crop productivity (Rahman *et al*., 2021; Ali *et al*., 2022; Nyaupane *et al*., 2024). The findings amply support that genotype selection synchronized with an appropriate irrigation schedule enhances growth, phenology, and grain yield.

Conclusions and Recommendations

The present research illustrates the importance of optimizing the irrigation time and genotype performance in improving wheat production under the subtropical climate of Bangladesh. Among the varieties tested, BARI Gom-32 and BARI Gom-25 produced the highest yield and agronomic performance under full irrigation conditions (I_3), while Protiva performed the lowest yield and its related traits. Strategic irrigation during crown root initiation, booting, and grain filling stages was crucial for increasing yield-related traits such as spike length, thousand-grain weight, and harvest index. Strong correlations between yield and its attributing traits, such as effective tiller number, spike length, and thousand-grain weight, affirm their value as yield indicators. Multivariate analyses ensured the interaction between genotype and irrigation, providing a strong basis for selecting varieties and irrigation regimes. These findings offer valuable guidance for developing water-efficient, high-yielding wheat to decrease import dependency and strengthen food security in Bangladesh.

Acknowledgments

The authors are thankful to the National Science and Technology (NST) fellowship, Ministry of Science and Technology, Government of Bangladesh, for the financial support.

Novelty of statement

This research provides new insights into the interactive effects of genotype and irrigation scheduling on wheat performance under subtropical agro-ecological conditions of Bangladesh. The study demonstrates that three-stage irrigation substantially enhances growth, phenology, and grain yield, particularly in BARI Gom-32, thereby contributing to climate-resilient and sustainable wheat production strategies.

Author's Contribution

Muntarina Hussan Mouri: Conceptualization, Investigation, Methodology, Project administration, Software, Data curation, Formal analysis, Resources, Visualization, Writing- original draft.
Mahadi Hasan Monshi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Writing- original draft.
Rehenuma Tabassum: Supervision, Formal analysis, Methodology, Conceptualization, Data curation, Visualization, Writing- original draft, review & editing.
Bright Gyamfi Adu: Formal analysis, Investigation, Methodology, Software, Writing- review & editing.
Hasan Mehraj: Data curation, Formal analysis, Resources, Methodology, Writing- review & editing.
Md. Shakhawat Hossain: Resources, Validation, Writing- review & editing.
Jahidul Hassan: Conceptualization, , Formal analysis, Investigation, Methodology, Writing- original draft.
Ahmed Khairul Hasan: Formal analysis, Resources, Validation, Writing- review & editing.
Fakhrul Islam Monsh: Fund acquisition, Conceptualization, Supervision, Investigation, Methodology, Project administration, Resources, Validation, Writing- original draft, Writing- review, editing, and finalizing the manuscript.

Generative AI or AI assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors declare no competing interests.

References

Acharjee, T.K. and M. Shariot-Ullah. 2021. Irrigation requirement and possibility of high-temperature stress of wheat for different planting dates under climate change in Bogura, Bangladesh. J. Bangladesh Agric. Univ., 19(2): 277-286. https://doi.org/10.5455/JBAU.41181

Ahmad, A. and R. Kumar. 2015. Effect of

irrigation scheduling on the growth and yield of wheat genotypes. Agric. Sci. Digest., 35(3): 199-202. http://doi.org/10.5958/0976-0547.2015.00045.2

Ahmed, Z., A. Kadir, R. Alam, H.A. Rezoan, and M.A.H. Laskor. 2025. The impact of staple crop price instability and fragmented policy on food security and sustainable development: a case study from Bangladesh. Discov. Sustain., 6: 79. https://doi.org/10.1007/s43621-025-00878-7

Ahmed, S.F., A. Nazran, T.K. Ghosh, J.U. Ahmed, and M. Mohi-Ud-Din. 2023. Screening drought-tolerant bread wheat genotypes using yield-based stress indices. Ann. Bangladesh Agric., 27(2): 72517.

Ali, N. and M. Akmal. 2022. Wheat growth, yield, and quality under water deficit and reduced nitrogen supply: A review. Gesunde Pflanzen., 74: 371-383. https://doi.org/10.1007/s10343-021-00615-w

Anjum, M.M., M. Arif, M. Riaz, K. Akhtar, S.Q. Zhang, and C.P. Zhao. 2021. Performance of hybrid wheat cultivars facing deficit irrigation under semi-arid climate in Pakistan. Agron., 11: 1976. https://doi.org/10.3390/agronomy11101976

Baloch, S.U., L. Liu, M.N. Kandhroo, S. Fahad, S.A. Sabiel, S.K. Baloch, S.A. Badini. 2014. Effect of different irrigation schedules on the growth and yield performance of wheat (*Triticum aestivum* L.) varieties. J. Biol. Agric. Healthcare., 4(20): 5-17.

Bapela, T., H. Shimelis, T.J. Tsilo, and I. Mathew. 2022. Genetic improvement of wheat for drought tolerance: Progress, challenges and opportunities. Plant., 11(10): 1331. http://doi.org/10.3390/plants11101331

Çebi, U., S. Özer, O. Öztürk, B. Aydın, and R. Çakır. 2023. Yield and water productivity of rice grown under different irrigation methods. J. Agric. Sci., 161: 387-397. https://doi.org/10.1017/S0021859623000308

Du, X., Z. Gao, X. Sun, D. Bian, J. Ren, P. Yan, and Y. Cui. 2022. Increasing temperature during early spring increases winter wheat grain yield by advancing phenology and mitigating leaf senescence. Sci. Total Environ., 812: 152557. https://doi.org/10.1016/j.scitotenv.2021.152557

FAO. 2025. GIEWS-global information and early warning system. Retrieved from http://faostat.fao.org/default.aspx (Accessed 15 April 2025).

Gomez, K.A. and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd ed. John Wiley & Sons, New York, USA. 704p. https://doi.org/10.1017/S0014479700014496

Hasan, M.M., M. Alauddin, M.A.R. Sarker, M. Jakaria, and M. Alamgir. 2019. Climate sensitivity of wheat yield in Bangladesh: Implications for the United Nations sustainable development goals 2 and 6. Land Use Policy., 87: 104023. https://doi.org/10.1016/j.landusepol.2019.104023

Hossain, A. and J.A. Teixeira da Silva. 2013. Wheat production in Bangladesh: its future in the light of global warming. AoB Plant., 5: pls042. http://doi.org/10.1093/aobpla/pls042

Ihsan, M.Z., F.S. El-Nakhlawy, S.M. Ismail, S. Fahad, and I. Daur. 2016. Wheat phenological development and growth studies as affected by drought and late season high temperature stress under arid environment. Front. Plant Sci., 7: 795. http://doi.org/10.3389/fpls.2016.00795

IPCC. 2019. IPCC special report. Climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Geneva, Switzerland.

Islam, M.T. and M. Nursey-Bray. 2017. Adaptation to climate change in agriculture in Bangladesh: The role of formal institutions. J. Environ. Manage., 200: 347-358. https://doi.org/10.1016/j.jenvman.2017.05.092

Islam, M.Z., M.A. Hakim, M.A. Kayum, M.M. Hossain, M.A. Alam, M.A. Kabir, M.M. Rahman, R. Islam, and R. Begum. 2019. Performance of eighteen advanced wheat lines grown under irrigated optimum and late sown conditions in different regions of Bangladesh. J. Multidiscip. Sci., 1(1): 1-9.

Lidwell-Durnin, J. and A. Lapthorn. 2020. The threat to global food security from wheat rust: ethical and historical issues in fighting crop diseases and preserving genetic diversity. Glob. Food Secur., 26: 100446.

Liu, X., B. Yin, X. Bao, X. Hou, T. Wang, C. Shang, M. Yang, and W. Zhen. 2024. Optimization of irrigation period improves wheat yield by regulating source-sink relationship under water deficit. Eur. J. Agron., 156: 127164.

Meena, R.P., K. Venkatesh, S.C. Tripathi, A. Jha,

R.K. Sharma, and G.P. Singh. 2019. Irrigation management strategies in wheat for efficient water use in the regions of depleting water resources. Agric. Water Manage., 214: 38-46.
Mian, M.A.K. and A.A. Begum. 2020. Performance and possibility of growing wheat varieties in Chalan Beel area. Bangladesh J. Agric. Res., 45(1): 21-27.
Mobeen, M., K.H. Kabir, U.A. Schneider, *et al.* 2025. Climate change perception, adaptation, and constraints in irrigated agriculture in Punjab and Sindh, Pakistan. Mitig. Adapt. Strat. Global Chan., 30: 23. https://doi.org/10.1007/s11027-025-10212-1
Mojid, M.A. 2019. Emerging challenges and way forward for irrigated agriculture of Bangladesh. Water Utility J., 21: 17-28.
Monteleone, B., I. Borzí, M. Arosio, L. Cesarini, B. Bonaccorso, and M. Martina. 2023. Modelling the response of wheat yield to stage-specific water stress in the Po Plain. Agric. Water Manage., 287: 108444. https://doi.org/10.1016/j.agwat.2023.108444
Monshi, F.I. and M.A. Malek. 2013. Evaluation of twelve mutants of rapeseed for earliness, seed yield and response to changing environments in M6 generation. Bangladesh J. Crop Sci., 24: 123-130.
Mottaleb, K.A., D.B. Rahut, G. Kruseman, and O. Erenstein. 2018. Wheat production and consumption dynamics in an Asian rice economy: The Bangladesh case. Eur. J. Dev. Res., 30: 252-275. https://doi.org/10.1057/s41287-017-0096-1
Mu, Q., H. Cai, S. Sun, S. Wen, J. Xu, M. Dong, and Q. Saddique. 2021. The physiological response of winter wheat under short-term drought conditions and the sensitivity of different indices to soil water changes. Agric. Water Manage., 243: 106475. https://doi.org/10.1016/j.agwat.2020.106475
Mutanda, M., H. Shimelis, V. Chaplot, *et al.* 2025. Agronomic performance and water use efficiency of newly developed wheat populations under drought-stressed and non-stressed conditions. Discov. Appl. Sci., 7: 176. https://doi.org/10.1007/s42452-025-06605-1
Nyaupane, S., M.R. Poudel, B. Panthi, A. Dhakal, H. Paudel, and R. Bhandari. 2024. Drought stress effect, tolerance, and management in wheat: a review. Cogent Food Agric., 10(1): 2296094. https://doi.org/10.1080/23311932.2023.2296094
Pantha, S., B. Kilian, H. Özkan, F. Zeibig, and M. Frei. 2024. Physiological and biochemical changes induced by drought stress during the stem elongation and anthesis stages in the Triticum genus. Environ. Exp. Bot., 228(B): 106047. https://doi.org/10.1016/j.envexpbot.2024.106047
Rahman, M.M., M.M. Alam, M.K. Aurangozeb, A. Hossain, and M.O. Kayess. 2024. Effects of different levels of irrigations on yield and yield contributing characters of wheat at Bangladesh condition. Asian J. Adv. Agric. Res., 24(10): 9-16. https://doi.org/10.9734/ajaar/2024/v24i10552
Rahman, M.A., S.A. Baly, M.A. Jahan, A.T. Shamsuddoha, S. Nusrin, S. Jahan, and M.S. Islam. 2021. Growth and yield performance of selected wheat genotypes at variable irrigation management. Int. J. Sci. Bus., 5(5): 139-149. https://ijsab.com/wp-content/uploads/733.pdf
Ratul, A.A., T.S. Hoque, M.R. Islam, and M.A. Hoque. 2021. Physico-chemical properties of acid soils from Madhupur Tract and Northern & Eastern Piedmont Plains of Bangladesh. Asian J. Med. Biol. Res., 7(1): 12-20. https://doi.org/10.3329/ajmbr.v7i1.53304
Rehman, A., Z. Batool, M. Ha, *et al.* 2024. Climate change and food security in South Asia: the importance of renewable energy and agricultural credit. Humanities Soc. Sci. Commun., 11: 342. https://doi.org/10.1057/s41599-024-02847-3
Sarker, K.K., A. Hossain, J. Timsina, S.K. Biswas, S.L. Malone, M.K. Alam, H.W. Loescher, and M. Bazzaz. 2020. Alternate furrow irrigation can maintain grain yield and nutrient content, and increase crop water productivity in dry season maize in sub-tropical climate of South Asia. Agric. Water Manage., 238: 106229. https://doi.org/10.1016/j.agwat.2020.106229
Sen, R., A.K. Choudhury, S. Akhter, S. Ishtiaque, M.A.H.S. Jahan, F. Ahmed, J.C. Biswas, M. Maniruzzaman, M.M.U. Miah, M.M. Rahman, N. Kalra, M.A. Aziz, and A.S.M.M.R. Khan. 2017. Simulating nitrogen and irrigation effects on wheat production in Bangladesh under changing climate. Am. J. Plant Sci., 8: 1593-1606. https://doi.org/10.4236/ajps.2017.87110

Sewore, B.M. and A. Abe. 2024. Genetic variability and trait associations in bread wheat (*Triticum aestivum* L.) genotypes under drought-stressed and well-watered conditions. CABI Agric. Biosci., 5: 64. https://doi.org/10.1186/s43170-024-00259-6

Sheel, P.R., M.A.H. Chowdhury, M. Ali, and M.A. Mahamud. 2016. Physico-chemical characterization of some selected soil series of Mymensingh and Jamalpur districts of Bangladesh. J. Bangladesh Agric. Univ., 13(2): 197-206. http://doi.org/10.3329/jbau.v13i2.28780

Si, Z., A. Qin, Y. Liang, A. Duan, and Y. Gao. 2023. A review on regulation of irrigation management on wheat physiology, grain yield, and quality. Plant., 12: 692. https://doi.org/10.3390/plants12040692

Tabassum, R., M.A. Malek, and F.I. Monshi. 2015. Assessment of genetic diversity of rapeseed mutants in diverse environments. Asian J. Agric. Res., 9(6): 325-333.

Tabassum, R., F.I. Monshi, M.S. Hossain, R. Roy, M.H. Monshi, and A.K. Hasan. 2023. Comparative assessment of selected exotic hybrid rice (*Oryza sativa* L.) based on quantitative traits analysis. Agric. Forest., 69(3): 39-48. https://doi.org/10.17707/AgricultForest.69.3.04

Wang, D., S. Liu, M. Guo, Y. Cheng, L. Shi, J. Li, Y. Yu, S. Wu, Q. Dong, J. Ge, *et al*. 2025. Optimizing nitrogen fertilization and irrigation practices for enhanced winter wheat productivity in the North China Plain: A meta-analysis. Plant., 14: 1686. https://doi.org/10.3390/plants14111686

Wang, Y., H. Sun, and L. Wang. 2024. Optimizing drip irrigation to enhance winter wheat performance: yield, economic benefits, and water use efficiency. Int. J. Agric. Sustain., 22(1): 2437214. https://doi.org/10.1080/14735903.2024.2437214

Yan, Z., W. Zhang, X. Liu, Q. Wang, B. Liu, and X. Mei. 2024. Grain yield and water productivity of winter wheat controlled by irrigation regime and manure substitution in the North China Plain. Agric. Water Manage., 295: 108731. https://doi.org/10.1016/j.agwat.2024.108731

Yesmin, M.A., M. Salim, F.I. Monshi, A.K. Hasan, A. Hannan, S.S. Islam, and R. Tabassum. 2022. Morpho-physiological and genetic characterization of transplanted Aman rice varieties under Old Brahmaputra Flood Plain (AEZ-9) in Bangladesh. Trop. Agric. Res. Ext., 25(1): 71-84.

You, Y., P. Song, X. Yang, Y. Zheng, L. Dong, and J. Chen. 2022. Optimizing irrigation for winter wheat to maximize yield and maintain high-efficient water use in a semi-arid environment. Agric. Water Manage., 273: 107901. https://doi.org/10.1016/j.agwat.2022.107901

Zhao, J., X. Xu, S. Liu, J. Jia, M. Li, H. Huang, G. Zhang, and C. Zhao. 2024. Optimizing wheat prosperity: Innovative drip irrigation and nitrogen management strategies for enhanced yield and quality of winter wheat in the Huang-Huai-Hai region. Front. Plant Sci., 15: 1454205. https://doi.org/10.3389/fpls.2024.1454205

Zhao, Z., Q. Li, F. Xia, P. Zhang, S. Hao, S. Sun, C. Cui, and Y. Zhang. 2025. Optimized water management strategies: Evaluating limited-irrigation effects on spring wheat productivity and grain nutritional composition in arid agroecosystems. Agric., 15: 1038. https://doi.org/10.3390/agriculture15101038

Zhuang, T., S.T. Ata-UI-Karim, B. Zhao, X. Liu, Y. Tian, Y. Zhu, W. Cao, and Q. Cao. 2024. Investigating the impacts of different degrees of deficit irrigation and nitrogen interactions on assimilate translocation, yield, and resource use efficiencies in winter wheat. Agric. Water Manage., 304: 109089. https://doi.org/10.1016/j.agwat.2024.109089