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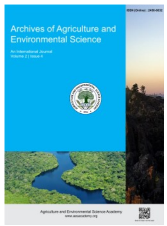

ORIGINAL RESEARCH ARTICLE

CrossMark

Enhancing wheat yield through strategic irrigation management

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ABSTRACT

To assess the irrigation strategies, an experiment was conducted with three wheat varieties viz. BARI Gom-19, BARI Gom-21, and BARI Gom-24 and four levels of irrigation viz. no irrigation (control), one irrigation at the crown root initiation (CRI) stage [17 days after sowing (DAS)], two irrigations at CRI (17 DAS) and the booting stage (52 DAS), and three irrigations at CRI (17 DAS), the booting stage (52 DAS), and the heading stage (67 DAS). Variety, irrigation and their association revealed notable impact on the yield of wheat. Within the three varieties tested, BARI Gom-24 demonstrated the highest performance, producing the greatest total tillers/hill (4.43), effective tillers/hill (3.75), grains/spike (40.55), 1000-grain weight (53.93 g), and grain yield (4.41 t/ha). Regarding irrigation, the best results were achieved with three irrigation applications, resulting in the tallest plants (96.22 cm), the highest total tillers/hill (4.79), effective tillers/hill (4.17), grains/spike (44.36), 1000-grain weight (55.38 g), and grain yield (4.35 t/ha). When combining variety and irrigation, BARI Gom-24 with three irrigations produced the tallest plants (99.13 cm), the highest total tillers/hill (4.93), effective tillers/hill (4.33), grains/spike (46.39), 1000-grain weight (55.80 g), and grain yield (4.41 t/ha). All these parameters showed significantly lower performance under no-irrigation conditions. The findings suggest that providing thrice irrigations at the CRI, booting, and heading stages is the optimal strategy for maximizing wheat yield with BARI Gom-24.

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INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most essential cereal crops globally, belonging to the Gramineae family. It is the most widely cultivated cereal, surpassing rice in production. It is often preferred over rice due to its higher protein content, making it a nutritionally rich staple food (Islam *et al.*, 2018). Wheat grains contain 12% protein, 1.72% fat, 69.60% carbohydrates, and 27.20% minerals, further highlighting their nutritional significance (BARI, 2006). In Bangladesh, wheat is the second most important cereal crop. However, despite its significance, the average yield remains lower than that of more developed nations. Several factors contribute to this low productivity, including the need for suitable wheat varieties, irrigation and other management practices (Pandey *et al.*, 2021). Varietal selection plays a vital role in wheat production, as high-quality varieties contribute to better seed quality and higher yields. Studies have shown that agronomic traits and yield performance can be significantly improved across different wheat cultivars (Sarwar *et al.*, 2010; Halder *et al.*, 2016; Moutussi *et al.*, 2021; Ashikuzzaman *et al.*, 2024).

Water scarcity also limits wheat production, reducing cultivation by about 30% due to an inadequate water supply (Islam *et al.*, 2016; Sarker *et al.*, 2018). With proper water and nutrient management, wheat production in Bangladesh could rise by up to 70% (Ahmed, 2006). Irrigation is essential for wheat growth and yield, as its frequency directly affects grain production. Research indicates that increasing irrigation frequency enhances yields (Khajanji & Swivedi, 1988; Ibrahim *et al*., 2010; Khatun *et al*., 2007), with critical timing during the crown root initiation (CRI) stage also playing a significant role in yield (Islam *et al*., 2018; Randhawa *et al*., 1976). In Bangladesh, limited and unpredictable rainfall during the *rabi* season complicates rainfed wheat cultivation, and inadequate irrigation facilities prevents consistent water supply (Islam *et al*., 2018). Therefore, effective water management at vital growth stages is crucial for improving yields. This study aims to assess the impact of different irrigation levels, providing insights into optimal irrigation strategies for better wheat production.

MATERIALS AND METHODS

Study location and experimentation

The research was carried out at Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh, which is situated at latitude 24° 75' N and longitude 90° 50' E. The experimental site is a part of the Old Brahmaputra Floodplain soil region (AEZ 9), with a pH of 6.5 and a low organic matter content of 1.3%. The area experiences high temperatures, humidity, and heavy rainfall during the summer, while winter is marked by moderate rainfall and relatively low temperatures (Figure 1).

Experimental treatments and design

Treatments consist of three varieties viz. BARI Gom-19, BARI Gom-21 and BARIGom-24 and four irrigations level viz. no irrigation (I_0), single irrigation (I_1) at CRI (17 DAS), double irrigations (I_2) at CRI (17 DAS) and booting stage (52 DAS) and three irrigations (I_3) at CRI (17 DAS), booting stage (52 DAS) and heading stage (67 DAS). The experiment employed a split-plot design assigning irrigation in the main plot and variety allocated in the sub-plots with three replications. There were a total of 36 unit plots, or 4 × 3 × 3. Each unit plot had a 4.0 m × 2.5 m^2 area and a 1.5 m interval between subplots. The blocks were placed 1.5 meters apart, while the major plots were divided by 1.0 metre. Within each replication, the treatments were allocated to the plots at random.

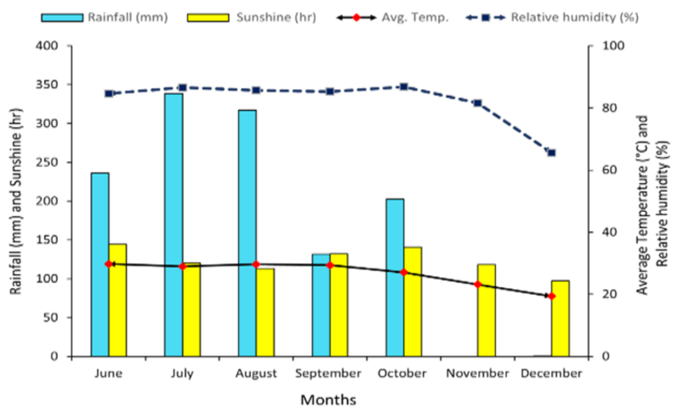

Figure 1. *Meteorological information of the experimental site.*

Crop management

The experimental field was initially ploughed on November 10, 2016, using a power tiller. Subsequently, the field was plowed and cross-plowed three times using a power tiller, followed by laddering to create a fine tilth. Before sowing, the entire field was sectioned into five unit plots, ensuring the necessary spacing was maintained. Fertilizers were applied at the rates of 220 kg/ha urea, 157 kg/ha TSP, 110 kg/ha MoP, and 110 kg/ha gypsum. One-third of the urea and the full amounts of TSP, MoP, and gypsum were mixed into the soil at the last step of land preparation. The individual plots were manually spaded, and the fertilizers were well mixed before sowing. The remaining 2/3 of the urea were applied in two equal portions, the first at 23 DAS and the second at the maximum tillering stage, 45 DAS, followed by irrigation. The sowing depth was carefully maintained for each treatment, and the seeds were enclosed with soil. Precautions were taken to protect the seedlings from birds for up to 15 DAS. Special care was taken about irrigation. Irrigation was applied after 17 DAS, 52 DAS and 67 DAS after sowing at CRI, at booting stage and at heading stages respectively, as per treatment specification. Some plots were not irrigated as those plots were treated without irrigation experiment. The experimental plots were sprayed on 11 DAS with insecticide Dimecron 100 E-C g 0.9-4 L ha^{-1} to control the wire worm (*Otenicer apruinincl*). No infestation of disease was found. Three weeding's were done, first one at 7 DAS, second one at 21 DAS and the last one at 35 DAS after sowing were done by hand pulling.

Data collection

The crop was fully matured and harvested on March 11, 2017. Maturity was identified when 85% of the grains had turned golden yellow. The fresh weights of grain and straw were measured from a 1.0 m² area in the middle of each plot after the crops had been threshed. Every plot's harvested crops were packed separately, properly tagged, and carried to the threshing floor. After cleaning, the grains weight was adjusted to meet the recommended moisture level of 14%. Grain and straw yields per plot were measured and converted to t/ha following the sun-drying of the straw. Additionally, five randomly chosen sample plants from each plot were examined for yield components and plant characteristics. The entire plot was measured for grain yield, harvest index (HI), biological yield, and straw yield.

Statistical analysis

The gathered information was compiled and arranged in preparation for statistical examination. MSTAT-C software was used to do the analysis of variance (ANOVA). The Duncan's Multiple Range Test (DMRT) was used to assess variations in treatment means. The graphs were illustrated by using the R (4.4.2) software.

RESULTS AND DISCUSSION

Plant height (cm)

The variety and level of irrigation had a notable impact on plant height (Table 1), whereas their interaction did not show a significant effect (Table 2). The tallest plant (87.82 cm) was recorded in BARI Gom-24 which was as good as BARI Gom-21, while the shortest plants (79.40 cm) were observed for BARI Gom-19. Within the irrigation levels, the tallest plant height (96.22 cm) was achieved with I_3, and the lowest (70.36 cm) with I_0. As the number of irrigations increased, plant height climbed steadily and peaked at three irrigations.

Number of total tillers/hill

Variety, irrigation levels, and their interactions greatly affected the total tillers/hill (Table 1). The greatest number of total tillers/hill (4.43) was noted for BARI Gom-24, while the lowest (4.14) was observed for BARI Gom-19. Among the irrigation levels, the maximum total tillers/hill (4.79) were achieved with I_3, and the minimum (3.77) with I_0. The total tillers/hill increased progressively with additional irrigations, reaching its peak at three irrigations. BARI Gom-24, irrigated three times, produced the maximum total tillers/hill (4.93), whereas the lowest (3.52) was recorded for BARI Gom-19 without irrigation (Table 2). These findings are consistent with previous studies by Haj et al. (2007), highlighting the importance of irrigation management and variety selection in optimizing rice yield parameters such as tiller production.

Number of effective tillers/hill

Variety and irrigation levels notably affected the effective tillers/hill (Table 1), whereas their interaction showed no notable effect. The most productive tillers/hill were produced by the BARI Gom-24 variety (3.75), while BARI Gom-19 recorded the lowest (3.55). Haj *et al.* (2007) examined the impact of different irrigation levels on wheat and reported significant variations in number of effective tillers/hill. Regarding irrigation treatments, the highest effective tillers/hill (4.17) was achieved with I_3, while the least (2.98) was noted without irrigation. Furthermore, the number of effective tillers/hill steadily increased with additional irrigations, reaching its highest at three irrigations.

Number of non- effective tillers/hill

The non-effective tillers/hill were not significantly affected by the variety. However, irrigation levels strongly influenced non-effective tillers/hill (Table 1). The highest number (0.79) was noted in I_0, while the lowest (0.56) was noted in I_3. However, the variety (Table 1) and the interaction between variety and irrigation levels (Table 2) did not have a notable effect on the non-effective tillers/hill. This suggests that irrigation management plays a more critical role than variety choice in minimizing non-effective tillers.

Number of grains/spike

Variety, level of irrigation and their interactions showed notable effect on grains/spike (Table 1). The varieties of BARI Gom-24 and BARI Gom-19 recorded the greatest (40.55) and lowest (35.78) grains/spike in the study. I_3 had the highest grains/spike (44.36), while I_0 had the lowest grains/spike (29.69). It was found that when the number of irrigations grew, the grain spike gradually increased as well, peaking at three irrigations. Three irrigations of BARI Gom-24 generated the highest grains/spike (46.39), whereas BARI Gom-19 without irrigation produced the lowest number (30.32) (Table 2). These findings align with Ibrahim *et al.* (2010), who reported similar grain production with three or four irrigations applied at 30-day intervals. This indicates that proper irrigation management, along with variety selection, plays a crucial role in maximizing grain yield.

Table 1. Impact of variety and Irrigation level on yield and yield contributing traits of wheat.

Treatment	Plant height (cm)	Total tillers/hill (no.)	Effective tillers/hill (no.)	Non-effective tillers/hill(no.)	Sterile spikelets spike^{-1}	Grains/ spike^{-} (no.)	1000-grain weight (g)	Biological yield (t/ha)	Harvest Index (%)
Variety									
BARI Gom-19	79.40^{b}	4.14^{b}	3.55^{b}	0.68	2.68^{a}	35.78^{c}	52.91	4.49^{c}	36.48^{c}
BARI Gom-21	83.88^{ab}	4.33^{a}	3.63^{a}	0.64	2.65^{a}	38.39^{b}	53.62	5.32^{b}	39.11^{b}
BARI Gom-24	87.82^{a}	4.43^{a}	3.75^{a}	0.60	2.41^{b}	40.55^{a}	53.93	5.95^{a}	40.99^{a}
Sig. level	*	**	**	NS	*	**	NS	**	**
CV (%)	4.72	1.95	2.39	6.86	12.81	1.70	2.74	3.39	4.32
Irrigation level									
I_0	70.36^{c}	3.77^{d}	2.98^{d}	0.79^{a}	2.91^{a}	29.69^{d}	52.27^{c}	4.25^{d}	37.77^{b}
I_1	80.93^{b}	4.13^{c}	3.51^{c}	0.63^{b}	2.63^{b}	38.93^{c}	53.23^{bc}	4.71^{c}	38.45^{b}
I_2	87.29^{b}	4.47^{b}	3.91^{b}	0.60^{b}	2.47^{bc}	41.97^{b}	54.31^{ab}	6.24^{b}	37.94^{b}
I_3	96.22^{a}	4.79^{a}	4.17^{a}	0.56^{b}	2.31^{c}	44.36^{a}	55.38^{a}	6.87^{a}	41.43^{a}
Sig. level	**	**	**	**	**	**	**	**	**
CV (%)	8.80	3.37	3.69	18.18	10.31	1.51	3.54	2.57	3.13

There is no statistical difference between values that have the same letters in the same column; **=Significant at 1% level of probability, * =Significant at 5% level of probability, NS = Not significant; V_1=BARI Gom-19, V_2=BARI Gom-21, V_3=BARI Gom-24, I_0= No irrigation, I_1 = Irrigation one time at CRI stage, I_2 = Irrigation two times at CRI and booting stage, I_3 = Irrigation three times CRI, booting stage and heading stage.

Table 2. Interaction impact of variety and irrigation on yield and yield contributing traits of wheat.

Interaction (Variety × Irrigation)	Plant height (cm)	Total tillers/hill (no.)	effective tillers/hill (no.)	Non-effective tillers/hill (no.)	Sterile spikelets/ spike	grains/ spike (no.)	1000- grain weight (g)	Biological yield (t/ha)	HI (%)
$V_1 \times I_0$	68.67	3.52^{d}	2.87	0.96	3.10	30.32^{h}	52.07	3.79^{h}	34.50^{f}
$V_1 \times I_1$	73.53	3.87^{c}	3.40	0.57	2.72	37.48^{f}	53.17	4.25^{g}	35.55^{ef}
$V_1 \times I_2$	82.80	4.47^{b}	3.87	0.60	2.53	40.80^{d}	54.03	5.98^{d}	37.24^{de}
$V_1 \times I_3$	92.60	4.73^{a}	4.07	0.66	2.39	42.50^{c}	54.43	6.34^{bc}	38.64^{cd}
$V_2 \times I_0$	72.00	3.93^{c}	3.07	0.86	2.55	32.38^{g}	52.40	4.60^{f}	39.79^{bc}
$V_2 \times I_1$	87.40	4.27^{b}	3.60	0.67	2.54	40.74^{d}	53.27	5.33^{e}	42.01^{ab}
$V_2 \times I_2$	91.93	4.47^{b}	3.93	0.54	2.40	42.88^{c}	54.37	6.56^{b}	39.10^{cd}
$V_2 \times I_3$	96.93	4.73^{a}	4.13	0.60	2.15	44.19^{b}	55.20	7.20^{a}	42.05^{a}
$V_3 \times I_0$	70.40	3.87^{c}	3.00	0.87	3.07	32.36^{g}	52.33	4.38^{fg}	39.03^{cd}
$V_3 \times I_1$	81.87	4.27^{b}	3.53	0.74	2.65	38.58^{e}	53.27	4.55^{f}	37.79^{cde}
$V_3 \times I_2$	87.13	4.47^{b}	3.93	0.53	2.48	42.22^{c}	54.33	6.18^{cd}	37.48^{cde}
$V_3 \times I_3$	99.13	4.93^{a}	4.33	0.46	2.10	46.39^{a}	55.80	7.39^{a}	43.59^{a}
Sig. Level	NS	*	NS	NS	NS	*	NS	**	*
CV (%)	8.80	3.37	3.69	18.18	10.31	1.51	3.54	2.57	3.13

There is no statistical difference between values that have the same letters in the same column; **=Significant at 1% level of probability,* =Significant at 5% level of probability, NS = Not significant; V_1=BARI Gom-19, V_2=BARI Gom-21, V_3=BARI Gom-2, I_0= No irrigation, I_1 = Irrigation one time at CRI stage, I_2 = Irrigation two times at CRI and booting stage, I_3 = Irrigation three times CRI, booting stage and heading stage.

Number of sterile spikelets/spike

Sterile spikelet/spike notably impacted by variety and irrigation (Table 1). The sterile spikelet/spike had the highest value (2.68) in BARI Gom-19 and the lowest value (2.41) in BARI Gom-24. I_0 had the greatest number of sterile spikelets/spike (2.91), followed by I_1 (2.63) and I_3 (2.31). It was shown that as irrigation decreased the number of sterile spikelets/spike decreased as well, reducing most at three irrigations. There was no discernible difference in the sterile spikelets/spike across variety and irrigation (Table 2).

1000-grain weight (g)

The 1000-grain weight was not notably impacted by the cultivar (Table 1). However, the 1000-grain weight varied notably across various irrigation treatments (Table 1). The highest grain weight was observed under the I_3 treatment (55.38 g), followed by I_2 (54.31 g), with the lowest recorded in I_0 (52.27 g). However, the interaction between variety and irrigation did not show a significant effect on 1000-grain weight (Table 2), suggesting that irrigation management plays a more crucial role than variety selection in determining grain weight.

Grain yield (t/ha)

The grain yield was significantly influenced by variety, irrigation levels, and their interactions (Figure 2). Varieties of different field crops showed comparable differences in crop characteristics, yield, and yield attributes (Paul *et al.*, 2019; Mahmud *et al.*, 2024). The highest grain yield (4.41 t/ha) was recorded for the BARI Gom -24 variety, while the lowest (2.87 t/ha) was observed for BARI Gom-19. These results aligned with those of (Rabbani *et al.*, 2023, Roy *et al.*, 2024). Among the irrigation treatments, the highest grain yield (4.35 t/ha) was achieved under I_3, which was statistically comparable to its yield under two irrigations whereas the lowest (2.87 t/ha) occurred under I_0. The findings showed that grain yield increased notably with the number of irrigations, peaking at three irrigations. Islam *et al.* (2018) observed the same findings in his studies. The synergistic effect of irrigation schedules to specific wheat varieties maximizes yield potential. Applying insufficient irrigation in several little amounts was not more successful than applying it in relatively big volumes, usually with one or two applications, according to Shao *et al.* (2009). Proper irrigation management, combined with suitable variety selection, is essential for enhancing wheat productivity.

Straw yield (t/ha)

Straw yield was notably influenced by the variety, irrigation levels, and their interactions (Figure 3). The variety BARI Gom-24 produced the most straw (5.36 t/ha), while BARI Gom-19 produced the least (3.21 t/ha). Out of all the irrigation treatments, I_3 produced the most straw (5.82 t/ha), while I_0 produced the least (2.64 t/ha). The findings showed a significant increase in straw yield with the number of irrigations, reaching its peak at three irrigations. Khan *et al.* (2009) and Gharib *et al.* (2009) documented the positive effects of higher irrigation levels on wheat straw yield. These studies underscore the importance of appropriate irrigation management in enhancing wheat production. Specifically, three irrigations applied at CRI, booting, and heading stages yielded the highest values across all measured parameters. Notably, BARI Gom-24, when provided with three irrigations, achieved the highest straw yield at 5.87 t/ha, which was statistically comparable to BARI Gom-21 under the same irrigation conditions. In contrast, the lowest straw yield (2.68 t/ha) was observed in BARI Gom-19 without irrigation.

Biological yield (t/ha)

Both irrigation levels and variety, as well as their interactions, had a substantial impact on biological yield. The variety BARI Gom-24 had the highest biological yield (5.95 t/ha), while BARI Gom-19 had the lowest (4.49 t/ha) (Table 1). Out of all the irrigation treatments, I_3 had the highest biological yield (6.87 t/ha), while I_0 had the lowest (4.25 t/ha) (Table 1). Notably, BARI Gom-24 with three irrigations yielded the highest biological yield (7.39 t/ha), while BARI Gom-19 without irrigation yielded the lowest straw yield (3.79 t/ha) (Table 2). Proper irrigation scheduling can significantly improve crop growth and biomass accumulation, ultimately contributing to higher overall productivity.

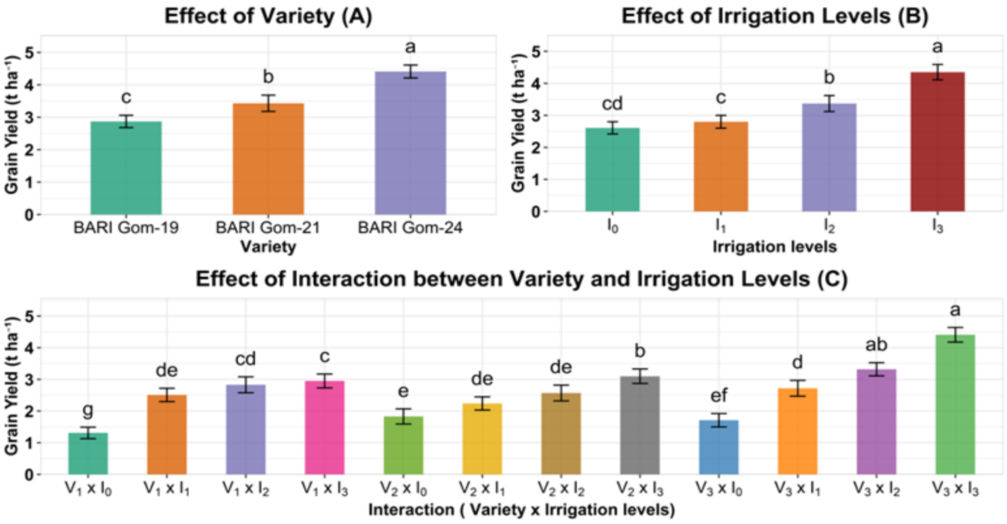

Figure 2. *Effect of variety (A), irrigation levels (B) and their interactions (C) on the grain yield of wheat.*

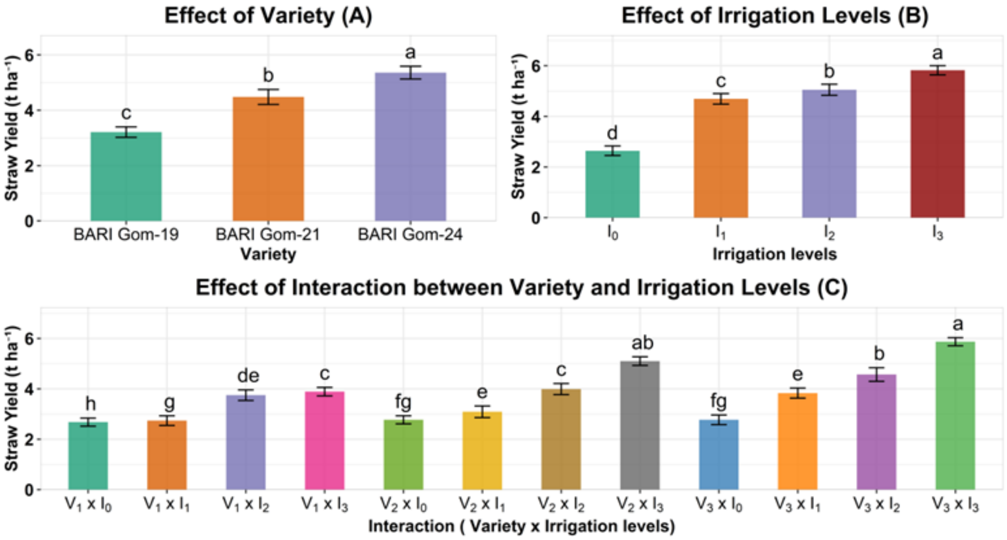

Figure 3. *Effect of variety (A), irrigation levels (B) and their interactions (C) on the straw yield of wheat.*

Harvest index (%)

Variety, irrigation levels, and their interactions all had a substantial impact on the harvest index. BARI Gom-19 had the lowest harvest index (36.48%), whereas BARI Gom-24 had the highest HI (40.99%) (Table 1). The highest harvest index (41.43%) among the irrigation treatments was noted under I_3, while the lowest (37.77%) was noted under I_0 (Table 1). Table 2 indicates that the combination of BARI Gom-24 with three irrigations resulted in the maximum harvest index (43.59%), whereas BARI Gom-19 without irrigation had the lowest (34.50%). These findings highlight the importance of both variety selection and irrigation management in optimizing the harvest index, emphasizing that adequate irrigation improves grain yield efficiency relative to total biomass production.

Conclusion

Among the three tested varieties, BARI Gom-24 exhibited superior performance across all yield-contributing parameters, including total tillers/hill, effective tillers/hill, grains/spike, 1000-grain weight, grain and straw yield. Similarly, irrigation significantly influenced wheat growth and productivity, with the highest yield obtained from the treatment involving three irrigations at CRI (17 DAS), booting (52 DAS), and heading (67 DAS) stages. The interaction effect between variety and irrigation further confirmed that BARI Gom-24 with three irrigations produced the best results in terms of yield components and grain yield. Conversely, the absence of irrigation led to a substantial reduction in all measured parameters. These findings underscore the importance of strategic irrigation scheduling, particularly the application of three irrigations, as an effective approach to enhance wheat (cv. BARI Gom-24) productivity.

DECLARATIONS

Author contribution statement

Conceptualization: M.S. and S.K.P., Methodology: M.S. and S.K.P.; Software and validation: S.C.R., S.K.S.; Formal analysis and investigation: S.K.S. B.R.D., Resources: M.S. and S.K.P.; Data curation: M.Z.I., S.K.S., Writing—original draft preparation: B.R.D. and S.C.R., Writing—review and editing: S.K.P. and S.K.S.; Visualization: M.S., Supervision: S.K.P.; Project administration: M.S. and S.K.P., Funding acquisition: S.K.P. All authors have read and agreed to the published version of the manuscript.

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Ethics approval: This study did not involve any animal or human participant and thus ethical approval was not applicable.

Consent for publication: All co-authors gave their consent to publish this paper in AAES.

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