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Comparative study of standard heterosis for yield and its attributes in bread wheat under two different water regimes

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Abstract

Water stress conditions have occurred in the past in various places of the world, affecting the yield and production of numerous crops, including wheat. The aim of this research was to estimate standard heterosis under two different water regimes for grain yield and its attributes in 33 crosses, which were obtained by crossing 11 lines and 3 testers in a Line × Tester mating design. The best cross combinations for yield and contributing traits under irrigated condition were C4, C8, C33, C24, and C23, compared to both checks HD2967 and PBW660. Whereas, in rainfed condition, C18, C14, C26, C21, and C20 crosses were superior to the checks. For both irrigated and rainfed conditions, the best cross combinations identified were C29, C15, C32, C2, and C31. As a result, these cross combinations could be used in wheat breeding programmes to improve bread wheat genotypes for increased grain yield, agro-morphological features, and water stress tolerance. The presence of high heterosis for yield-contributing traits not only aids in the development of hybrids by exploiting heterosis but also in the production of transgressive segregants to develop elite lines.

Introduction

Bread wheat (*Triticum aestivum* L.) is one of the world's major cereal crops, with global production of 769.6 million tonnes in 2021 (FAO, 2021*a*). Wheat is currently second only to rice in terms of volume consumed, with 67% of the wheat produced going to food, 21% to animal feed, and the rest going to other uses such as industrial biofuels (FAO, 2021*b*). By 2050, the world's population is predicted to reach nine billion people, necessitating a 60% increase in wheat productivity (United Nations, 2019). To address this problem, wheat yields must be increased from 1% per year to at least 1.6% per year (Giraldo *et al.*, 2019). This is made more difficult by irregular rainfall patterns predicted for climate change, which are expected to result in an increase in droughts (IPCC, 2019). The impact on final yield is, however, dependent on the growth stage as well as the intensity and duration of stress events (Sarto *et al.*, 2017). Abiotic factors such as drought, salinity and heat stress, rather than biotic factors, are the primary causes of wheat output losses (Abhinandan *et al.*, 2018; Chaudhary *et al.*, 2022). Recurrent drought conditions have threatened world wheat production, and immediate action is needed to address this. Water stress has diverse effects on wheat at different growth stages (Khadka *et al.*, 2020), and the duration and intensity of water stress can impair wheat development for many traits (Sarto *et al.*, 2017), ultimately reducing grain yield.

Drought is divided into three categories meteorological, agricultural and hydrological droughts. Meteorological drought is caused by anomalies in the atmosphere and higher temperatures; agricultural drought is caused by low precipitation and high evapotranspiration rates; and hydrological drought is caused by water sources falling below their normal average (Bakke *et al.*, 2020). The rainfed condition is a hydrological drought, where the development of crops depends on rainfall. Water stress has a negative impact on crop development, dry matter production and prospective yield (Zhang *et al.*, 2018). The effect of water stress depends on the growth stages of wheat as well as the duration and intensity of water stress (Daryanto *et al.*, 2016; Sarto *et al.*, 2017). Using a wide range of testing environments, both normal and stressed, may be more appropriate and efficient in identifying the genotype that has adapted to water stress conditions. By lowering dependency on final grain yield, measuring yield attributing traits independent of grain yield enhances selection efficiency. Utilizing the potential for additive gene action this technique may enhance the likelihood of creating more successful crossings in a breeding effort (Dolferus *et al.*, 2019).

The future potential of wheat hybrid technology is dependent on male-sterility systems, floral biology, combining ability, heterosis and economic level exploitation that can be utilized to break yield restrictions and boost productivity in the country's key wheat-growing area

(Basnet *et al.*, 2022). The selection of parents based on their mean performance may not always result in the desired outcomes (Riaz *et al.*, 2021). As a result, the use of heterosis, or hybrid vigour, in the wheat crop might be considered one of the key breakthroughs in plant breeding because it produces superior traits in the offspring compared to the parents. Furthermore, the extent to which heterosis can be used is largely determined by the direction and degree of heterosis (Begna, 2021). Heterosis demonstrates the parents' potential to combine traits and is used in breeding programmes. In practical plant breeding, standard heterosis is more important than heterobeltiosis and relative heterosis because it aims to develop desired hybrids superior to the existing high-yielding commercial varieties (Lingaiah *et al.*, 2023). Estimation of heterosis in wheat crop has also been reported by Saren *et al.* (2018) and Gimenez *et al.* (2021) for grain yield, plant height, productive tillers, days to heading and several other agro morphological traits. Wheat production will likely increase by generating new cultivars with a broader genetic base and better performance in changing environments (Tadesse *et al.*, 2019; Langridge and Reynolds, 2021). In order to develop high-yielding climate-resilient cultivars the ability of a genotype to perform well in both a normal and stressful environment should be identified. This study compares several bread wheat crosses made using the Line × Tester mating design under two distinct water regimes with the aim of calculating standard heterosis. The best heterotic combinations with resilient traits were identified here for yield and yield-attributing traits using standard heterosis estimations in stress and normal environments. These cross-combinations can be used for the exploitation of heterosis by identifying transgressive segregants from the advanced generation, which could be important in wheat breeding programmes for tolerance to water stresses and yield improvement.

Material and methods

Plant genetic material

The present investigation was undertaken to study the heterosis for grain yield and its component of bread wheat genotypes using line × tester (L × T) analysis under irrigated (E1) and rainfed (E2) conditions. The crosses were made between 11 lines and three testers (Table 1) in L × T mating design. The genotypes used for crossing contained drought-tolerant wheat varieties suitable for growing in rainfed condition *viz.*, UP2572, VL3001, PBW644, C306, WH1080, WH1142 and PBW644.

Experimental trial

Forty-nine genotypes comprising 11 lines, 3 testers, 33 F1s and 2 checks (Tables 1 and 2) were planted in completely randomized block design with three replications in two environments i.e. irrigated (E1) and rainfed (E2) conditions at G. B. Pant University of Agriculture and Technology, Pantnagar in 2018-19 during *Rabi* season. The experimental materials for irrigated and rainfed conditions were planted on two different sowing dates. E1 was sown in mid of November, while E2 was in the first week of October. Pantnagar falls in a humid subtropical zone having the miscellaneous type of soil texture, which is generally 1.0–1.5 m deep. The favourable climatic condition for the normal growth of wheat crop is 20–25°C temperature throughout the crop duration with equitable distribution of rainfall. In this study, only a single irrigation was applied at tillering stage, after that no irrigation was applied to keep the experiment under moisture stress. While in irrigated condition, four irrigations were applied during the crown root initiation stage, tillering stage, flowering stage and dough stage for proper growth of the wheat genotypes. The water requirement is 450–650 mm for the whole production period of the wheat crop (Tadesse *et al.*, 2017). During this experiment in the whole Rabi season, the total rainfall was 75.8 mm (Fig. 1). In the rainfed environment (E2), it is shown in Fig. 1 that there was no rain from the tillering to the booting stage (November to January). According to the metrological data (Fig. 1), stress criteria are met for the E2 environment.

Table 1. List of parents and checks

S.No.	Genotypes
Lines	
1	BECARD/KACHU
2	BOW/VEE/5/ND/VG9144//KAL/BBB/YACO/4/CHIL/6/CASKOR/3/…
3	92.001E7.32.5/SLVS/5/NS-732/HER/3/PRL/SARA//TSI/VEE#5/…
4	FRANCOLIN#1/BAJ#1
5	KACHU*2//WHEAR/SOKOLL
6	PRL/2*PASTOR//PBW343*2/KUKUNA/3/ROLF07/4/BERKUT//…
7	UP2572
8	VL3001
9	NW5054
10	PBW644
11	C306
Testers	
1	WH1080
2	WH1142
3	HD3086
Checks	
1	HD2967
2	PBW660

Measurement of agronomic traits

Data was taken on 14 morphological characters *viz.*, days to 75% heading, days to maturity, plant height (cm), peduncle length (cm), awn length (cm), tillers per plant, flag leaf area (cm^2), spike length (cm), spikelets per spike, grains per spike, grain weight per spike (g), 1000 grain weight (g), biological yield per plant (g) and grain yield per plant (g). The flag leaf area was calculated using the following formula according to Singh (1970).

Leaf area = Leaf length × Width × 0.7238

Computation of drought susceptibility index

Fischer and Maurer's (1978) formula was used to calculate the drought susceptibility index (DSI) for yield character per cross.

$$DSI = (1-Xi/X)/(1-Yi/Y)$$

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Table 2. List of cross combinations

S.No.	Crosses	Designation
1	BECARD/KACHU × WH1080	C1
2	BECARD/KACHU × WH1142	C2
3	BECARD/KACHU × HD3086	C3
4	BOW/VEE/5/ND/VG9144//KAL/BBB/YACO/4/ CHIL/6/CASKOR/3/… × WH1080	C4
5	BOW/VEE/5/ND/VG9144//KAL/BBB/YACO/4/ CHIL/6/CASKOR/3/… × WH1142	C5
6	BOW/VEE/5/ND/VG9144//KAL/BBB/YACO/4/ CHIL/6/CASKOR/3/… × HD3086	C6
7	92.001E7.32.5/SLVS/5/NS-732/HER/3/PRL/ SARA//TSI/VEE#5/… × WH1080	C7
8	92.001E7.32.5/SLVS/5/NS-732/HER/3/PRL/ SARA//TSI/VEE#5/… × WH1142	C8
9	92.001E7.32.5/SLVS/5/NS-732/HER/3/PRL/ SARA//TSI/VEE#5/… × HD3086	C9
10	FRANCOLIN#1/BAJ#1 × WH1080	C10
11	FRANCOLIN#1/BAJ#1 × WH1142	C11
12	FRANCOLIN#1/BAJ#1 × HD3086	C12
13	KACHU*2//WHEAR/SOKOLL × WH1080	C13
14	KACHU*2//WHEAR/SOKOLL × WH1142	C14
15	KACHU*2//WHEAR/SOKOLL × HD3086	C15
16	PRL/2*PASTOR//PBW343*2/KUKUNA/3/ ROLF07/4/BERKUT//… × WH1080	C16
17	PRL/2*PASTOR//PBW343*2/KUKUNA/3/ ROLF07/4/BERKUT//… × WH1142	C17
18	PRL/2*PASTOR//PBW343*2/KUKUNA/3/ ROLF07/4/BERKUT//… × HD3086	C18
19	UP2572 × WH1080	C19
20	UP2572 × WH1142	C20
21	UP2572 × HD3086	C21
22	VL3001 × WH1080	C22
23	VL3001 × WH1142	C23
24	VL3001 × HD3086	C24
25	NW5054 × WH1080	C25
26	NW5054 × WH1142	C26
27	NW5054 × HD3086	C27
28	PBW644 × WH1080	C28
29	PBW644 × WH1142	C29
30	PBW644 × HD3086	C30
31	C306 × WH1080	C31
32	C306 × WH1142	C32
33	C306 × HD3086	C33

where, Xi represents phenotypic means for each cross under a stressed condition, X represents phenotypic means for each cross under a control condition, Yi represents phenotypic means for all the crosses under a stressed condition, Y represents phenotypic means for all the crosses under control condition.

Estimation of heterosis

The mean data was subjected to L × T analysis as per Kempthorne (1957). The standard heterosis, expressed as a per cent increase or decrease in the performance of F_1 hybrid over check parent, was computed for each character using the following formula:

$$\text{Standard heterosis} = \frac{\overline{F}_1 - \overline{CP}}{\overline{CP}} \times 100$$

where,

$\overline{F}_1$ = Mean performance of F_1 hybrid

$\overline{CP}$ = Mean performance of check parent

The significance of heterosis was tested with the 't' test as given below:

For standard heterosis $t = \frac{\overline{F}_1 - \overline{CP}}{\sqrt{2Me/r}}$

Where, Me = Error mean square; r = Number of replications.

Violin plot for the density distribution of standard heterosis was drawn using the R-package 'ggplot2' (Wickham, 2016).

Results

The mean performance and analysis of variance revealed that all the wheat genotypes differ significantly for all the traits in both irrigated (E1) and rainfed (E2) conditions, and genotype × environment (G × E) interaction was significant for all the traits except peduncle length. In the present study, crosses were examined for standard heterosis over both checks for yield and it's contributing traits in both environments. The density distribution graph for standard heterosis is shown by a violin plot for two checks and two environments in the respective figures (Fig. 2). The heterosis of cross combinations for all the traits in both conditions is explained for each trait as follows.

Days to 75% heading and days to maturity

The Standard heterosis (%) over the check HD2967 for days to 75% heading ranged from −8.33 to 5.80 in E1 and from −16.34 to 0.65 in E2 environments (Fig. 2). The highly significant negative heterosis for this trait was found in crosses C4, C10 and C12 (−8.33) in E1, whereas C6 (−16.34) was followed by C11(−15.03) in E2. For days to maturity, heterosis over the check HD2967 ranged from −6.85 to 0.51 in E1 and −5.15 to −0.23 in E2. Significant negative heterosis for this trait was demonstrated by crosses C4 (−6.85), followed by C28 (4.26) in E1, whereas crosses C18 (−5.15), followed by C11, and C23 (−4.92) were identified in E2.

For days to 75% heading in E1 and E2, the heterosis (%) over check PBW660 ranged from −1.94 to 13.18 and from −10.49 to 7.7, respectively. For days to maturity, over the same check the heterosis ranged from −2.39 to 5.32 and −4.71 to 0.23 in E1 and E2, respectively (Fig. 2). Crosses C6(−10.49) followed by C11(−9.09) showed highly significant negative heterosis for days to 75% heading in E2 but in E1 did not have any crosses with significant negative heterosis. Whereas, cross C4(−2.39) in E1 and crosses C18(−4.71) followed by C11, C14, C23 and C33(−4.47) in E2 were identified of days to maturity.

Plant architecture (Cm/Cm^2)

The range of heterosis values over the check HD2967 and PBW660 for the attributes related to plant architecture *viz.*, plant height, peduncle length, awn length, flag leaf area and

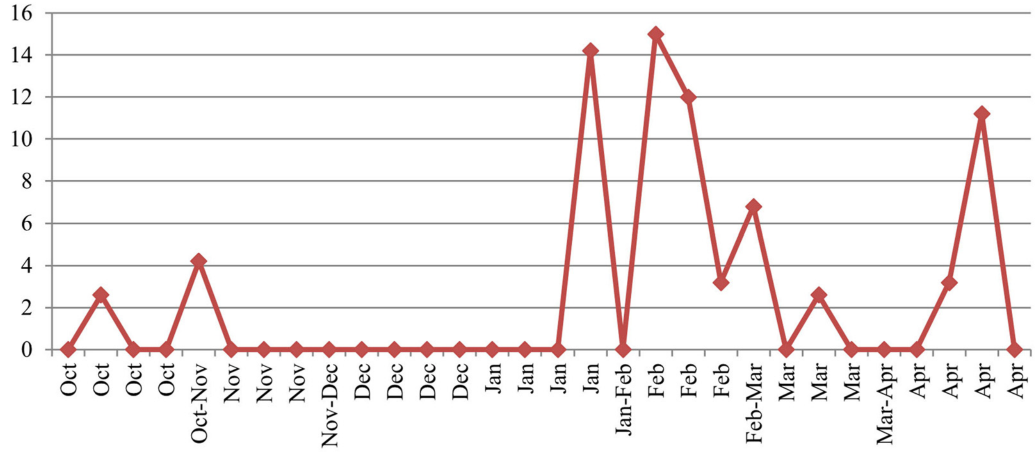

Figure 1. Graph showing monthly rainfall pattern (mm) during the wheat season in 2018-19.

spike length are represented in Fig. 2. For plant height, the highest significant negative heterosis over check HD2967 was shown by crosses C15 (−16.46) followed by C1 (−12.04) in E1 and crosses C14 (−16.19) followed by C24 (−14.88) in E2. Whereas, the highest significant negative heterosis over check PBW660 was shown by crosses C15 (−16.77), followed by C1 (−12.36), in E1, and cross C14 (−4.37) in E2. For another yield attribute, peduncle length, standard heterosis over the check HD2967 was shown by crosses C2 (−16.20) followed by C1 (−16.05) in E1, and in E2, none of the crosses showed significant negative heterosis.

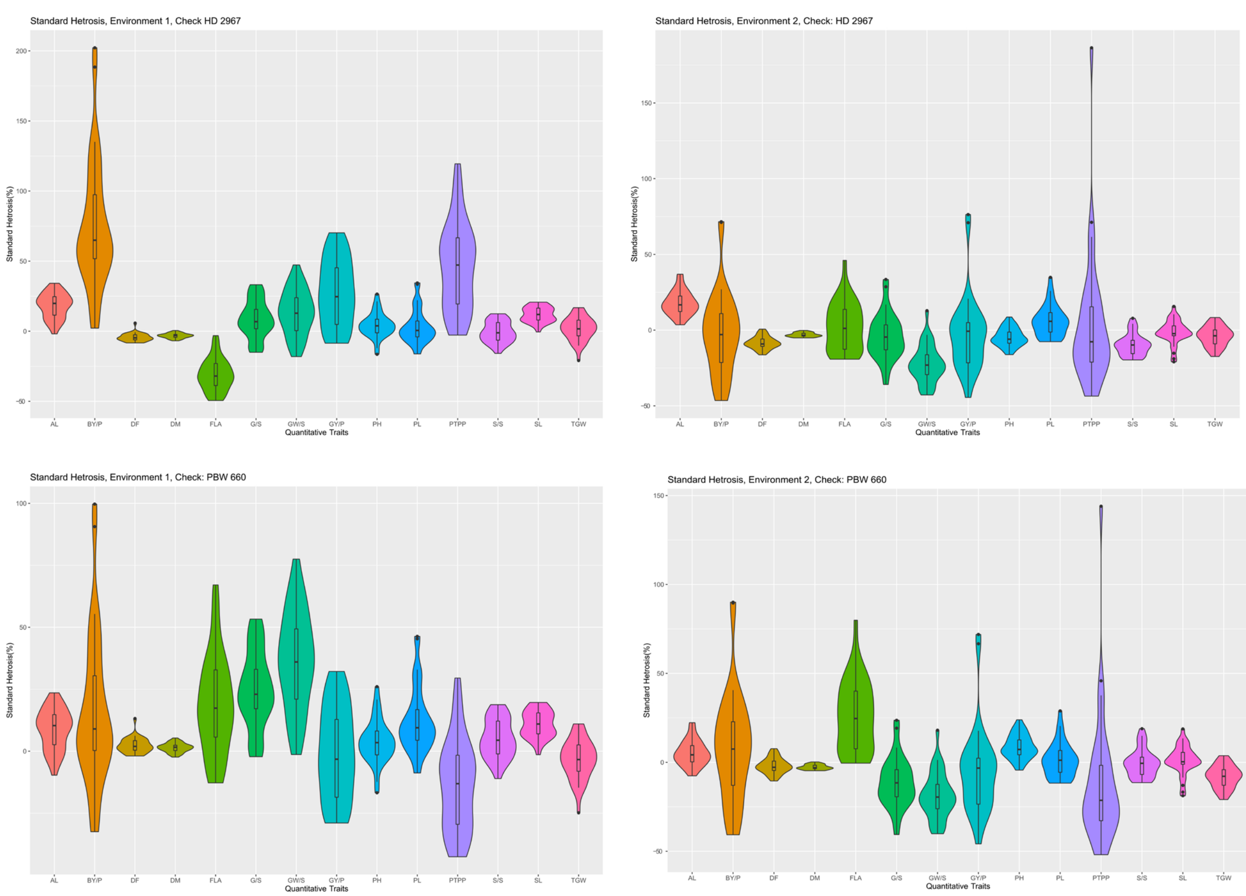

Figure 2. Density distribution of standard heterosis over the checks HD2967 and PBW660 for yield and its component traits in the irrigated and rainfed conditions. Box plot within the violin represents the mean of all standard heterosis values. Environment1, Irrigated condition; Environment2, rainfed condition; AL, awn length; BY/P, biological yield per plant; DF, days to 75% heading; DM, days to maturity; FLA, flag leaf area; G/S, grains/spike; GW/S, grain weight/spike; GY/P, grain yield/plant; PH, plant height; PL, peduncle length; PTPP, productive tillers/plant; S/S, spikelets/spike; SL, spike length; TGW, 1000 grain weight.

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Whereas, for this trait in both environments, cross C2 (−8.79 in E1 and −11.68 in E2) showed the highest significant negative heterosis over the check PBW660.

Flag leaf area and awn length are important plant attributes that affect photosynthesis. For the flag leaf area, significant positive heterosis over check HD2967 was observed in C15 (46.02), followed by C14 (29.22) in E2, but it's not identified in any crosses in E1. Whereas, for the same trait, C15 (67.09 in E1 and 79.89 in E2) showed the highest significant positive heterosis over check PBW660 in both environments, followed by C23 (58.87) in E1 and C14 (59.20) in E2. For the yield attribute awn length, over both the checks HD2967 and PBW660, C8 (34.20 and 23.53, respectively) followed by C32 (31.46 and 21.02, respectively) in E1, and crosses C26 (36.93 and 22.30, respectively) followed by C27 (35.70 and 21.20, respectively) in E2 showed the highest significant positive heterosis.

In another attribute, spike length, crosses C21 (20.73), followed by C32 (20.49) in E1 and C32 (15.64) in E2 demonstrated the highly significant positive heterosis over check HD2967, respectively. Whereas, the highest significant positive standard heterosis over check PBW660 showed by crosses C32 (19.42), followed by C21 (19.66) in E1, and crosses C32 (18.79) followed by C20 (13.44) in E2.

Yield and yield components

Numerical yield attributes such as productive tillers/plant, spikelets/spike and grains/spike are crucial. For all of these traits, Fig. 2 illustrates the range and mean of heterosis values over the check HD2967 and PBW660. For productive tillers/plants, the highly significant positive standard heterosis over the check HD2967 was observed in cross C33 (119.44), followed by C32 (102.78), in E1, and cross C21 (186.41) followed by C4 (71.18), in E2. Whereas, significant positive heterosis over check PBW660 for the same trait was observed in cross C33 (29.53), followed by C1 (18.05), in E1, and cross C21 (144), followed by C4 (45.83), in E2. In another numerical yield component, spikelets/spike, C24 (12.46) in E1 and cross C29 (7.81) in E2 had highly significant positive heterosis over the check HD2967. Whereas, for the same trait over the check PBW660, it was shown by crosses C8 and C24 (18.78), followed by C23 (16.58) in E1, and crosses C29 (18.90), followed by C5 (14.88) in E2. For grains/spike the highly significant positive heterosis over the check HD2967 was reported in crosses C24 (33.20), followed by C23 (32.79), in E1, and crosses C15 (33.42), followed by C29 (28.63), in E2. For the same trait, C15 (23.65) followed by C29 (19.21) in E1 and crosses C24 (53.30) followed by C23 (52.83) in E2 demonstrated the highly significant positive heterosis over the check PBW660.

The yield and its contributing traits were measured in weight are 1000 grain weight, grain weight per spike, grain yield/plant and biological yield/plant. The range and mean of heterosis values for these traits are shown in Fig. 2. For 1000 grain weight, the same crosses (crosses C31 followed by C4) showed the highest significant positive heterosis over both the checks in E1 environment. While in E2, cross C31 (8.33), followed by C22 (5.83), showed highly significant positive heterosis over check HD2967, and none of the crosses showed significant positive heterosis over check PBW660 for this trait. For grain weight per spike, crosses C23 and C24 showed the highest significant positive heterosis over both checks in E1, whereas only the C29 cross showed significant positive heterosis in E2. For grain yield/plant, the highest significant positive heterosis over check HD2967 was observed in cross C29 (70.23) in E1 and cross C20 (76.29) in E2. While C29 (32.18) and C17 (26.74) in E1 and C20 (71.90) and C21 (66.67) in E2, respectively, had the highest significant positive heterosis over the check PBW660. In another yield trait, biological yield/plant, crosses C33 (202.22) followed by C32 (188.47) in E1 and crosses C21 (71.56) followed by C20 (71.16) in E2 had highly significant positive heterosis over check HD2967. Whereas crosses C33 (99.71) followed by C32 (90.62) showed highly significant positive heterosis over check PBW660 in E1, and crosses C21 (90.01) followed by C20 (89.57) in E2.

Discussion

Our investigation advances understanding of how morphological traits are affected by different water regimes, which is important in selecting the best genotype to be utilized in the breeding programmes (Sarto *et al.*, 2017). The results demonstrate that for all traits except peduncle length, there was a significant G × E interaction, and the performance of each genotype was different in irrigated and rainfed environments. Crosses C4 and C18 demonstrated highly significant negative heterosis in both irrigated and rainfed conditions for days to maturity. The importance of negative heterosis for days to 75% heading and days to maturity has been highlighted because early flowering and maturity are responsible for the drought escape mechanism in wheat plants (Shavrukov *et al.*, 2017). Early maturation and heading are essential in the breeding programme of wheat crop Saren *et al.*, (2018), Sharma *et al.* (2018), Shamuyarira *et al.*, (2019), Bapela *et al.*, (2022).

Crosses C15 and C14 showed highly significant negative heterosis over the check in both the irrigated and rainfed conditions, respectively, for plant height, similar to the reports of Saren *et al.* (2018) and Gimenez *et al.* (2021). To reduce water requirements and prevent moisture loss owing to transpiration, drought-tolerant plants have a reduced height. As a result, smaller plants exhibit less growth reduction than larger plants, implying that smaller plants are less sensitive to water stress (Nazir *et al.*, 2021). Khadka *et al.*, (2020) also reported that water stress affects different stages of growth.

In the present study, crosses C8 and C26 had longer awns in E1 and E2 environments. Under drought, awns retain a greater relative water content and photosynthetic electron transport rate than flag leaves, indicating that they are more resistant to soil moisture deficits (Maydup *et al.*, 2014). Green awns also contribute to the photosynthetic area and positively influence grain yield (Rebetzke *et al.*, 2016). Cross C15 was identified as the best heterotic cross for the flag leaf area. Flag leaf plays a major role in photosynthesis, thus, flag leaf area is important for grain filling (Ma *et al.*, 2021). Sharma *et al.* (2018) also reported positive heterosis for the flag leaf area. In irrigated and rainfed conditions, crosses C33 and C21 showed the highest significant positive heterosis over both the checks for tillers/plant. Tillering and stem elongation stages are critical for maintaining the number of spikelets per plant and spikes per plant, both of which directly affect grain yield. As a result, the severe drought during wheat tillering and stem elongation affects the number of grains per spike, and finally grain yield (Ding *et al.*, 2018). Patel (2018), Adhikari *et al.* (2020) also reported significant positive heterosis for productive tillers in their studies. C2 was determined to be the best cross combination across the two checks for short peduncles, which is considered an adaptive trait in wheat for water stress conditions and is also responsible for shorter plant height

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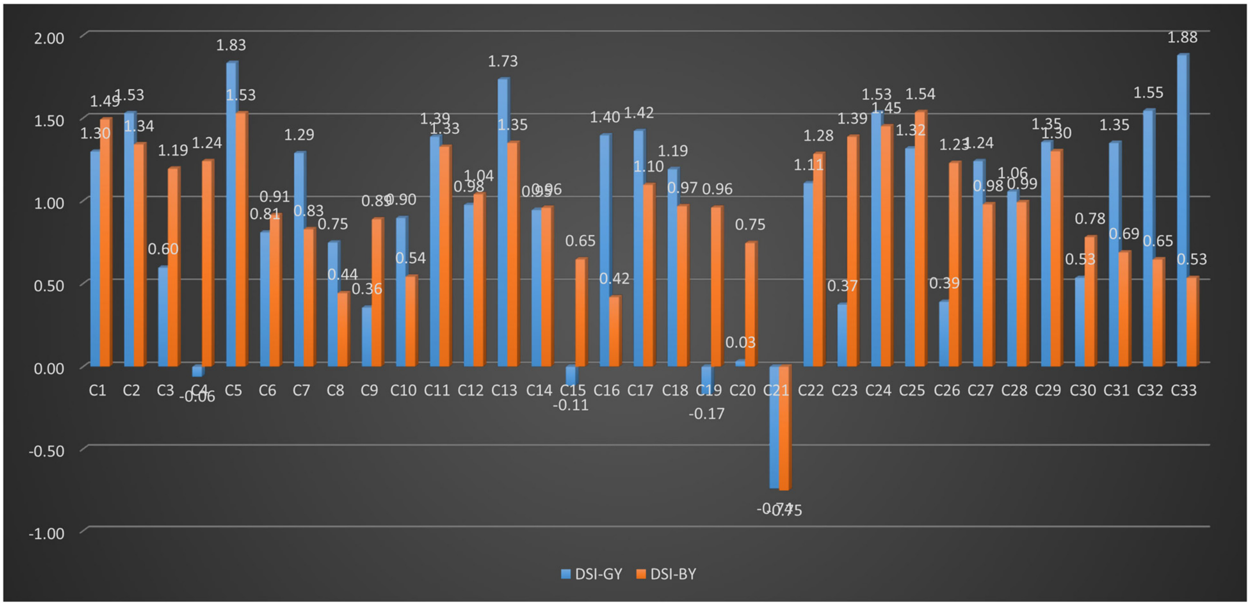

Figure 3. Drought Susceptibility Index (DSI) based on mean performance of hybrids under irrigated and rainfed conditions. DSI-GY, Drought Susceptibility index for grain yield; DSI-BY, Drought Susceptibility index for biological yield.

(Nazir *et al.*, 2021). Patel *et al.* (2015) have previously reported on the role of negative heterosis on peduncle length.

Crosses C21 and C32 showed standard positive heterosis over checks in E1 and E2 for spike length, whereas for spikelets per spike C24, C8 and C29 were the best cross combinations. The spike-related characters i.e. spike length, spikelets per spike, grains per spike, 1000 grain weight, grain weight per spike are essential component characters of yield; positive heterosis for these characters is desirable for increasing yield and these traits are influenced under water stress condition (Khadka *et al.*, 2020; Chaudhary *et al.*, 2023). Significant positive heterosis for spike length and spikelets per spike was in agreement with the findings of El-Gammaal and Yahya (2018), Patel (2018), Nagar *et al.* (2019), Ibrahim *et al.* (2020), Khaled *et al.* (2020). Crosses C24 and C15 were the best cross combinations in both environments for grains per spike. Positive heterosis for grains per

Table 3. Promising heterotic crosses for various characters

	Heterosis summary			
	Check HD2967		Check PBW660	
Character	E1	E2	E1	E2
Days to 75% heading	C4, C10 and C12(−8.33)	C6 (−16.34)	x	C6 (−10.49)
Days to maturity	C4(−6.85)	C18(−5.15)	C4(−2.39)	C18(−4.71)
Plant height (cm)	C15(−16.46)	C14(−16.19)	C15(−16.77)	C14(−4.37)
Spike length (cm)	C21(20.73)	C32 (15.64)	C32(19.42)	C32(18.79)
Peduncle length (cm)	C2(−16.20)	x	C2(−8.79)	C2(−11.68)
Awn length (cm)	C8(34.20)	C26(36.93)	C8(23.53)	C26(22.30)
Tillers/plant	C33(119.44)	C21(186.41)	C33(29.53)	C21(144)
Spikelets/spike	C24(12.46)	C29(7.81)	C8 and C24(18.78)	C29(18.90)
Flag leaf area (cm^2)	x	C15(46.02)	C15(67.09)	C15(79.89)
1000 grain weight	C31(16.79)	C31(8.33)	C31(10.99)	x
Grains/spike	C24(33.20)	C15(33.42)	C24(53.30)	C15(23.65)
Grain weight/spike	C23(47.30)	C29(12.82)	C23(77.50)	C29(18.06)
Biological yield/plant	C33(202.22)	C21(71.56)	C33(99.71)	C21(90.01)
Grain yield/plant	C29(70.23)	C20(76.29)	C29(32.18)	C20(71.90)

E1, Irrigated condition; E2, Rainfed condition; x, Indicate none of the entries found in desirable direction over the checks, Parenthesis values indicates % heterosis over check in desirable direction.

spike was also reported by Sharma *et al.* (2018), and Ibrahim *et al.* (2020).

Higher grain yield is the primary objective of wheat breeding. For the 1000 grain weight, cross C31 was identified as the best heterotic cross. Salam *et al.* (2019), Ibrahim *et al.* (2020), and Gimenez *et al.* (2021) also reported significant positive heterosis for this trait. For grain weight per spike, C23 and C29 were identified as the best cross combinations over both the checks in irrigated as well as rainfed conditions. Sharma *et al.* (2018) reported similar findings for this trait. The crosses C29 and C20 were identified as the best cross combinations for grain yield in both irrigated and rainfed conditions. Positive heterosis for grain yield was also reported by Thomas *et al.* (2017), Saren *et al.* (2018), Salam *et al.* (2019), Ibrahim *et al.* (2020) and Gimenez *et al.* (2021). Over both the checks, C33 was the best heterotic crossover for biological yield under irrigated condition, whereas C21 was identified under rainfed condition. In general biological yield positively correlated with economic yield and so positive heterosis is desired for this trait (Motawea, 2017).

The DSI is a crucial factor in determining which genotypes are drought tolerant. It is a measure of drought, based on loss of yield under drought conditions in comparison to the yield under normal conditions. The effects of water stress on grain yield and biological yield are shown in Fig. 3. Based on that for grain yield C3, C4, C6, C8, C9, C10, C12, C14, C15, C19, C20, C21, C23, C26 and C30 crosses showed <1 DSI. Whereas, for biological yield C6, C7, C8, C9, C10, C14, C15, C16, C18, C19, C20, C21, C27, C28, C30, C31, C32 and C33 cross combinations showed <1 DSI. From these tolerant cross combinations, C20 for grain yield whereas C21 and C33 for biological yield also showed the highest positive heterosis. Hence, these heterotic crosses can withstand water stress with minimum loss in yield.

In summary, this investigation advances understanding of important traits contributing to wheat yield under irrigated and rainfed condition. Overall, under the irrigated condition, crosses C4, C8, C33, C24 and C23, were identified as the best heterotic cross over both checks HD2967 and PBW660 for yield and its attributes. While, in rainfed condition crosses C18, C14, C26, C21 and C20 were best heterotic combinations over both the checks. For both irrigated and rainfed conditions, the best cross combinations identified were C29, C15, C32, C2, and C31. The best cross combinations under irrigated and rainfed conditions for yield and its attributed (Table 3) can be employed in future wheat breeding programmes to generate cultivars with high yield and water stress tolerance.

Conclusions

In conclusion, results revealed that crosses showed varied performance under irrigated and rainfed environments. For both environments, the best cross combinations for yield and its attributes were PBW644 × WH1142, KACHU*2//WHEAR/SOKOLL × HD3086, C306 × WH1142, BECARD/KACHU × WH1142, and C306 × WH1080. Cross combinations UP2572 × WH1142 for grain yield, UP2572 × HD3086 and C306 × HD3086 for biological yield showed the highest positive heterosis with <1 DSI. Therefore, these heterotic hybrids can tolerate water stress with minimum yield loss. The identified cross combinations can be exploited in future wheat breeding programme for obtaining higher yields and selection could be exercised in segregating generations for developing water stress-tolerant genotypes. The tolerance of these crosses and their performance under water stress conditions can be studied further by physiological and biochemical studies.

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Ethical statements. Hereby, I Divya Chaudhary consciously assure that for the manuscript ‘Comparative study of standard heterosis for yield and its attributes in bread wheat under two different water regimes’ the following is fulfilled:

1) This material is the authors’ own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors’ own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

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