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Trait Based Selection of Elite Wheat Genotypes under Irrigated, Heat Stress, and Heat Drought Conditions

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ABSTRACT

Environmental factors affects yield and yield-attributing parameters of wheat. To explore direct and indirect association and to identify the most appropriate trait for trait based selection of elite wheat genotypes under irrigated, heat stress and heat drought conditions, correlation, path and principal component analysis were performed. The field experiment was conducted using serpentine alpha lattice design at the agronomy farm of the Institute of Agriculture and Animal Science (IAAS), Paklihawa campus, Nepal that comprised of twenty elite wheat genotypes. The grain yield of wheat was found to have significant negative association with days to heading (DTH) and days to booting (DTB) under all tested conditions. Plant height (Ph) was found to have a significant negative association with grain yield of wheat under irrigated conditions while significant positive association was observed across heat stress and heat drought conditions ($p \leq 0.05$). DTB, DTH, and Ph had a direct influence on the yield across all tested conditions. For the breeding program, dwarf genotypes that are earlier in booting and heading should be promoted under irrigated conditions whereas the taller genotypes that are earlier in booting and heading should be promoted under heat stress and heat drought conditions. Based on selected traits, BL 4919 and NL 1350 were selected as high yielding genotypes under irrigated condition, NL 1369 and NL 1417 under heat stress condition and NL 1350 and Bhrikuti under the heat drought condition. These genotypes should be promoted in the varietal improvement program of Nepal to release as a potential climate resilient variety.

1. Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop in the world (Shewry and Hey, 2015). It contributes 15-20% of the total calorie requirement and is the major staple crop of 35% of the global population (Wieser et al., 2020). It ranks third position in terms of production in Nepal with a production of 2.99 tons per hectare. The net productivity of wheat in Nepal is comparatively lower as compared to India (3.47 tons per hectare), and China (5.81 tons per hectare). Wheat is cultivated in various environments in Nepal (Chatrath et al., 2007). Variation in the growing environment creates variation in yield through G x E interaction. Temperature and water are the key yield-limiting factors in wheat production (Rahaie et al., 2013). Wheat requires 266.8-500 mm of water (Deo et al., 2017). About 52% of the wheat-cultivated area of Nepal is weather dependent for irrigation due to poor infrastructure and uneven rainfall patterns of Nepal (Shiferaw et al., 2013). Whereas 25% total wheat growing area suffers from heat stress as a result of the late sowing (Upadhyaya and Bhandari, 2022). Wheat production is reduced by up to 60% and 46% under moisture stress and heat stress conditions, respectively (Fahad et al., 2017).

The trend of wheat production from 1961 to 2011 shows, only a 12-13 % increment in the total cropping area to feed a doubled population of 3.5 billion in 1961 to 7 billion population in 2011. In 2021/22, the global production of 778 million metric tons of wheat was not still enough to feed 14% (1.1 billion) of people suffering from chronic hunger in the world (Bhandari et al., 2023). Since the majority of the cropping lands are being converted to residential areas due to population growth, increasing yield through increasing cropping area is difficult (Bhanu, 2018). In the past 20 years, the productivity of wheat in Nepal had just increased by 1.2 tons per hectare from 1.79 in 2000 to 2.99 tons per hectare in 2021 and the population has increased by 25% from 24 million in 2000 to 30 million in 2021 . Whereas, the area under wheat cultivation has only risen by 7.73 % from 660,040 ha in 2000 to 711,067 ha in 2021. By 2050, the demand for wheat is predicted to increase by 25% whereas the yield is predicted to reduce by 44-47% due to climate-induced

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drought and heat stress (Abhinandan et al., 2018; Lesk et al., 2016; Liu et al., 2016). Hence, the prevalence due to hunger and malnutrition is predicted to aggravate further in Nepal. Since increasing total cropping area is difficult to achieve higher production and climate change is inevitable, heat stress and drought breeding are crucial for the food and nutritional security of the world.

Food security, eradication of hunger, and improving nutrition are the major aims of the Agriculture Development Strategy (ADS) and Sustainable Development Goals (SDG 2.0) (Bhandari et al., 2023). Wheat being the most diversified and most consumed cereal, has a significant role in eradicating global hunger and malnutrition. The production of wheat being mainly affected by abiotic stresses, it is very crucial to develop climate-resilient genotypes. The yield of wheat being a complex trait, had a direct and indirect association among various quantitative parameters.

Agronomic traits such as, days to booting, days to heading, days to anthesis, plant height, spike length, spikes per meter square, spikelets per spike, grains per spike, spike weight, and thousand kernel weight have been found to contribute to yield improvement of wheat (Bhandari et al., 2023; Bustos et al., 2013; Chen et al., 2012). Since the genetic progress under low-yielding stress conditions is lower in comparison to the high-yielding environment (Crespo-Herrera et al., 2018; Joudi et al., 2014; Lopes et al., 2012), that makes targeted trait-based breeding crucial for successful yield improvement program (Mwadzingeni et al., 2017; Tshikunde et al., 2019).

High-yield potential agronomic and phenological traits-based breeding has been deployed to identify high-yield potential wheat breeding lines (Aisawi et al., 2015; De Vita et al., 2007; Gao et al., 2017; Lopes et al., 2012; Manès et al., 2012). Since the production of wheat must increase from 3 to 5 t/ha with an annual growth rate of 1.3% by 2050 to meet the food demand (Poudel et al., 2020; Sharma et al., 2012), it is crucial to identify genotypes with desirable traits (Liu et al., 2015; Lopes et al., 2012). The present study aims to explore the association among agromorphological traits of wheat genotypes across different wheat growing environments to better understand the traits and help plant breeders create a desired combination for the trait-based selection of climate-resilient wheat genotypes (Khan and Dar, 2010; Upadhyay, 2020).

2. Materials and Methods

The experiment was conducted at the Institute of Agriculture and Animal Science (IAAS), Paklihawa campus, Rupandehi, Nepal in 2021. The experimental site lies at the geographic location of 27°29'02''N and 83°27'17'' E and an altitude of 104 meters above sea level. The Meteorological status of the site during the experimental year was taken from the Department of Hydrology and Meteorology (DHM), Bhairahawa. The Meteorological data of the experiment duration is presented in (Figure 1).

The genotypes were set up in an alpha lattice design with five blocks replicated twice for each irrigated, heat stress, and heat-drought condition. There were three Bhairahawa lines (BL), fifteen Nepal lines (NL), and two commercial checks Bhrikuti and Gautam provided by National Wheat Research Program (NWRP), Bhairahawa.

The phenological, growth, and yield-attributing data were collected through field observations of wheat. The days to 50% booting (DTB), days to 50% heading (DTH), and days to 50% anthesis (DTA) were recorded. Plant height (Ph) and spike length (SL) were measured from the base of the plant to the tip of the spike and from the bottom of the spike to the top of uppermost floret, respectively. The number of spikes per meter square (NSPMS), spikelet per spike (SPS), grains per spike (GPS), spike weight (TSW), thousand-grain weight (TKW), and grain yield (GY) were obtained by counting and weighing the relevant components of the harvested plants in each plot.

The irrigated condition was created by providing six standard doses of irrigation at pre-sowing, crown root initiation (CRI), Jointing, booting, milking, and soft dough stage. Heat stress is created by sowing wheat genotypes one month later (25 December) than irrigated condition (25 November) so that, the reproductive stage of the wheat synchronizes to high temperature at March- April (Figure 1). A heat drought condition was created by sowing the genotypes a month later without artificial irrigation except at the pre-sowing stage.

Descriptive statistics were done for all agronomic traits using Microsoft Excel 2021. Pearson's correlation coefficients were calculated among all pairs of agronomic traits to evaluate their interrelationships using SPSS V 26.0. Principal component analysis (PCA) was conducted in PAST 4.03 to reduce the dimensionality of the data and identify the underlying factors that explain the variability in the dataset. The PCA was conducted on the correlation matrix of the agronomic traits, and the number of principal components to retain was determined using the Kaiser-Guttman criterion (eigenvalues greater than 1). The factor loadings of the agronomic traits on the extracted principal components were used to identify the traits that have the highest contribution to each principal component.

Path analysis was performed using the matrix method in Microsoft Excel 2021 to assess the direct and indirect effects of agronomic traits on yield. The direct and indirect effects of each agronomic trait on wheat yield were quantified using the standardized path coefficients, and the relative importance of each trait was evaluated by comparing their direct and indirect effects on yield. All statistical analyses were performed at a 95% confidence level.

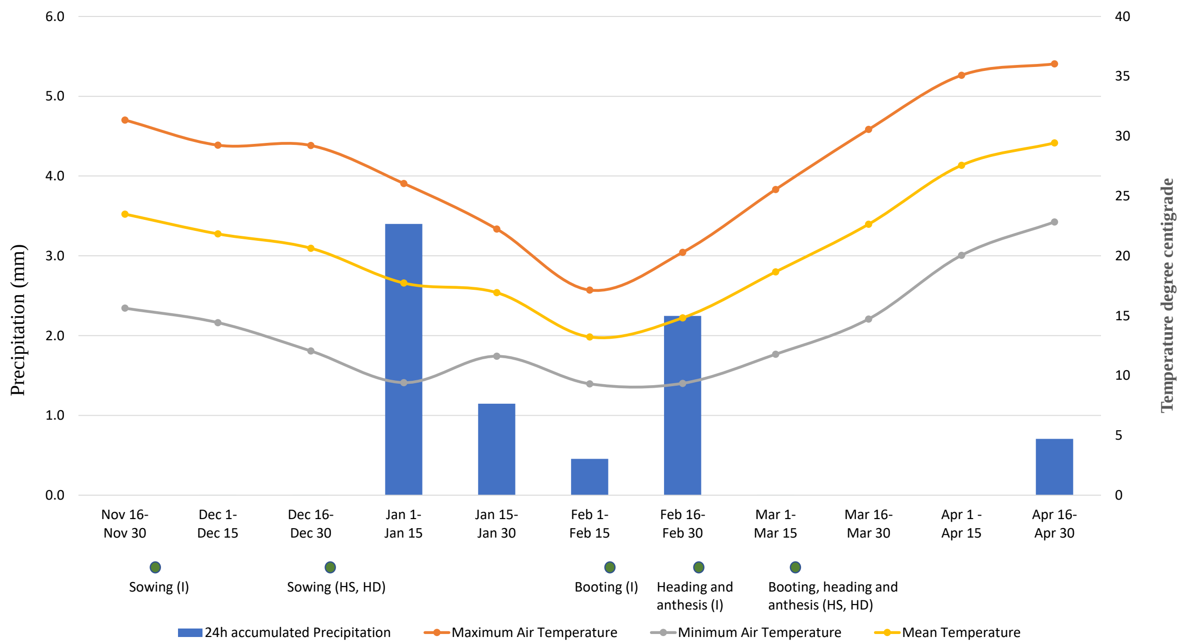

Figure 1. Agro meteorological parameters during the experimented year.

Table 1. Plant materials used for the study

S. N.	Genotypes*	Source	Released year	S. N.	Genotypes*	Source	Released year
1	Bhrikuti	CIMMYT, Mexico	1994	11	NL 1376	CIMMYT, Mexico	not released yet
2	BL 4407	Nepal	not released yet	12	NL 1381	CIMMYT, Mexico	not released yet
3	BL 4669	Nepal	not released yet	13	NL1384	CIMMYT, Mexico	not released yet
4	BL 4919	Nepal	not released yet	14	NL 1386	CIMMYT, Mexico	not released yet
5	Gautam	Nepal	2004	15	NL 1387	CIMMYT, Mexico	not released yet
6	NL 1179	CIMMYT, Mexico	not released yet	16	NL 1404	CIMMYT, Mexico	not released yet
7	NL 1346	CIMMYT, Mexico	not released yet	17	NL 1412	CIMMYT, Mexico	not released yet
8	NL1350	CIMMYT, Mexico	not released yet	18	NL 1413	CIMMYT, Mexico	not released yet
9	NL 1368	CIMMYT, Mexico	not released yet	19	NL 1417	CIMMYT, Mexico	not released yet
10	NL 1369	CIMMYT, Mexico	2018	20	NL 1420	CIMMYT, Mexico	not released yet

*The pedigree information of the genotypes are confidential and is maintained at National Wheat Research Program (NWRP).

3. Results

3.1. Performance of wheat genotypes under irrigated conditions

Wheat genotypes had an average yield of 4262.9 kg ha^{-1}, 3413.3 kg ha^{-1}, and 2577.5 kg ha^{-1} under irrigated, heat stress, and heat drought conditions, respectively. BL 4919 (6254.0 kg ha^{-1}), NL 1368 (4261.5 kg ha^{-1}), and Bhrikuti (3322.8 kg ha^{-1}) were the highest yielding wheat genotypes under irrigated, heat stress, and heat drought condition, whereas, NL 1420 (3164.0 kg ha^{-1}), NL 1387 (2513.8 kg ha^{-1}), and NL 1179 (1883.4 kg ha^{-1}) were the lowest yielding genotypes under irrigated, heat stress, and heat drought conditions (

Table 2, Table 3, Table 4).

3.2. Performance of wheat genotypes under heat stress conditions

The grain yield of wheat was reduced by 18.7% under heat stress condition as compared to irrigated. Bhrikuti (1.1%) had the least yield reduction while BL 4919 (39.4%) had the highest yield reduction under heat stress condition as compared to irrigated (Table 3, Table 5).

3.3. Performance of wheat genotypes under heat drought conditions

Wheat yield was further aggravated under heat drought condition due to the additional effect of low moisture stress on wheat. Wheat yield was reduced by 38.7% under heat drought condition as compared to irrigated while yield reduction was 24.2% under heat drought condition as compared to heat stress (Table 4, Table 5).

3.4. Correlation and path coefficient analysis

3.4.1. Irrigated conditions

The grain yield of wheat was found to be significantly negatively correlated with Ph, DTH, and DTB under irrigated condition (p≤0.05) (Table 6).

Table 2. Performance of wheat genotypes under irrigated conditions

Treatment	DTB	DTH	DTA	Ph (cm)	SL (cm)	NSPMS	NSPS	NGPS	TSW (g)	TKW (g)	GY (kg ha^{-1})
Bhrikuti	76	83	88	102.8	11.2	340	17.2	44.1	21.4	46.1	3828.3
BL 4407	72	84	88	93.6	10.7	343	17.3	36.5	22.9	47.8	3957.1
BL 4669	78	86	91	97.1	9.8	380	18.1	44.5	19.6	44.1	4612.8
BL 4919	71	80	87	91.3	11.1	366	18.7	49.1	23.7	49.3	6254.0
Gautam	83	90	91	96.4	10.5	350	16.9	44.4	20.7	35.7	3704.8
NL 1179	78	86	91	96.3	9.7	331	18.3	45.4	23.9	35.2	3848.8
NL 1346	71	80	85	90.5	10.4	369	17.0	48.9	21.3	38.7	5046.8
NL 1350	70	79	84	111.3	11.7	337	16.5	44.4	22.8	40.7	4181.4
NL 1368	82	87	91	93.6	9.9	337	18.9	48.5	20.7	30.5	4395.3
NL 1369	79	87	92	104.1	11.1	290	18.2	46.7	28.2	40.4	4393.8
NL 1376	79	86	91	94.9	8.9	339	16.0	41.5	24.6	48.5	4097.5
NL 1381	76	86	90	98.9	9.3	362	19.7	54.4	24.3	37.6	4427.4
NL 1384	85	91	97	100.7	10.4	426	19.3	49.0	22.9	37.8	3611.5
NL 1386	83	91	97	101.3	10.2	374	18.2	38.6	19.2	38.3	4202.5
NL 1387	79	88	92	101.4	10.5	347	18.3	49.4	25.2	38.8	4155.5
NL 1404	77	85	90	100.1	9.3	392	15.8	43.9	18.9	37.1	4866.0
NL 1412	79	90	91	102.7	10.5	433	19.0	43.3	24.1	39.6	4634.9
NL 1413	81	90	91	100.4	11.2	456	21.1	55.5	25.9	35.8	4069.5
NL 1417	78	89	92	105.5	11.0	223	19.8	53.3	27.1	40.3	3805.2
NL 1420	84	89	92	101.1	9.9	373	17.8	50.0	23.7	34.0	3164.4
Max	85	91	97	111.3	11.7	456	21.1	55.5	28.2	49.3	6254.0
Min	70	79	84	90.5	8.9	223	15.8	36.5	18.9	30.5	3164.4
Mean	78	86	91	99.2	10.4	358	18.1	46.6	23.1	39.8	4262.9
STD	4	4	3	5.1	0.7	50	1.3	4.9	2.5	5.0	647.2
CV	6	4	4	5.1	7.2	14	7.4	10.5	11.0	12.7	15.2

Maximum (Max), minimum (Min), standard deviation (STD), coefficient of variation (CV)

Table 3. Performance of wheat genotypes under heat stress conditions

Treatment	DTB	DTH	DTA	Ph (cm)	SL (cm)	NSPMS	NSPS	NGPS	TSW (g)	TKW (g)	GY (kg ha^{-1})
Bhrikuti	66	71	74	101.2	13.4	327	18.3	47.3	24.0	36.6	3723.0
BL 4407	67	71	73	90.2	10.9	319	16.4	41.6	22.5	34.9	3021.5
BL 4669	69	74	75	90.2	10.0	404	17.8	46.7	20.2	33.5	3521.0
BL 4919	64	70	73	99.3	10.3	348	18.2	52.0	24.2	33.5	3788.5
Gautam	69	74	75	94.0	9.5	381	16.6	41.5	19.9	32.5	3129.5
NL 1179	68	73	76	86.7	9.8	368	17.7	49.1	21.4	38.9	3204.5
NL 1346	65	71	74	90.0	10.2	387	17.2	46.1	20.9	33.8	3476.5
NL 1350	64	70	73	110.3	12.8	264	15.4	46.6	30.1	45.6	3567.0
NL 1368	69	73	77	88.7	10.0	316	18.6	42.8	18.9	35.6	4261.5
NL 1369	70	74	76	90.4	11.1	263	19.0	46.8	26.2	40.1	3434.0
NL 1376	69	74	76	93.8	9.7	339	16.3	41.8	19.1	34.6	3464.5
NL 1381	67	72	74	91.9	9.7	331	17.8	52.3	21.0	30.8	3308.5
NL 1384	70	74	77	96.5	11.2	400	18.3	43.4	16.3	28.4	3322.5
NL 1386	70	74	77	90.7	9.4	345	17.9	32.5	21.2	38.6	3414.0
NL 1387	69	74	76	91.3	10.2	311	17.7	46.9	20.8	33.3	2513.8
NL 1404	66	71	74	91.5	8.9	391	17.6	38.1	16.6	34.2	3408.5
NL 1412	68	73	76	97.4	10.1	359	17.7	38.0	17.6	33.5	3594.5
NL 1413	69	74	76	90.8	9.6	346	17.6	43.3	18.7	30.6	3266.0
NL 1417	67	73	76	94.9	10.7	267	18.7	54.6	25.9	34.4	3717.0
NL 1420	69	73	76	94.7	9.2	391	17.6	41.5	16.5	31.7	3130.0
Max	70	74	77	110.3	13.4	404	19.0	54.6	30.1	45.6	4261.5
Min	64	70	73	86.7	8.9	263	15.4	32.5	16.3	28.4	2513.8
Mean	68	73	75	93.7	10.3	343	17.6	44.6	21.1	34.8	3413.3
STD	2	1	1	5.3	1.1	44	0.9	5.3	3.6	3.8	350.3
CV	3	2	2	5.7	10.9	13	5.0	11.9	17.0	11.0	10.3

Table 4. Performance of wheat genotypes under heat drought conditions

Treatment	DTB	DTH	DTA	Ph (cm)	SL (cm)	NSPMS	NSPS	NGPS	TSW (g)	TKW (g)	GY (kg ha^{-1})
Bhrikuti	68	72	74	103.9	11.6	313	17.8	51.0	24.0	37.5	3322.8
BL 4407	67	72	74	96.7	11.4	348	17.3	48.2	21.5	36.7	2551.0
BL 4669	69	73	75	90.7	9.6	356	19.8	41.6	18.3	32.6	2216.7
BL 4919	64	71	75	109	11.7	296	20.9	51.1	27.5	42.9	3084.1
Gautam	70	73	75	100.7	9.7	385	18.9	44.0	20.0	37.3	2203.9
NL 1179	69	73	75	92.7	9.7	351	19.6	48.2	19.0	34.0	1883.4
NL 1346	67	72	74	98.9	11.0	379	18.3	50.8	21.7	35.7	2858.9
NL 1350	63	70	74	110.1	13.6	232	17.0	47.6	26.0	45.9	2825.2
NL 1368	68	73	75	94.1	9.7	334	18.7	48.9	20.5	35.7	2410.9
NL 1369	69	73	75	100	10.5	377	20.0	40.4	23.0	40.4	2337.8
NL 1376	68	73	75	97.4	10.6	319	18.1	44.8	22.5	37.3	3092.6
NL 1381	66	70	74	95.5	10.5	341	19.5	58.6	27.0	33.9	2293.9
NL 1384	69	74	76	99.4	11.2	416	18.3	47.0	18.7	32.5	2552.2
NL 1386	71	75	76	96.1	10.4	391	18.0	36.3	19.9	42.9	2621.4
NL 1387	68	73	76	96.1	10.8	339	18.9	49.1	21.6	36.0	2184.5
NL 1404	68	71	74	98.9	9.8	458	18.5	41.2	19.0	36.8	2584.4
NL 1412	69	73	75	100.1	10.1	371	18.8	42.0	19.0	36.9	2751.3
NL 1413	70	73	75	98.4	10.3	393	18.2	46.7	20.0	36.1	2739.7
NL 1417	68	73	75	101.1	10.4	309	19.5	50.4	23.6	34.2	2662.3
NL 1420	68	73	74	96.7	9.4	344	16.7	40.1	17.0	33.9	2373.0
Max	71	75	76	110.1	13.6	458	20.9	58.6	27.5	45.9	3322.8
Min	63	70	74	90.7	9.4	232	16.7	36.3	17.0	32.5	1883.4
Mean	68	73	75	98.8	10.6	353	18.6	46.4	21.5	37.0	2577.5
STD	2	1	1	4.8	1	48	1.1	5.2	3	3.6	355.3
CV	3	1	1	4.9	9.4	13.6	5.9	11.2	14.0	9.7	13.8

Table 5. Percentage yield reduction of wheat genotypes under heat stress and heat drought conditions as compared to irrigated and heat stress

	Yield performance (kg ha^{-1})			Percentage reduction		
	I	HS	HD	I vs HS	HS vs HD	I vs HD
Bhrikuti	3828.3	3723	3322.8	2.8	10.7	13.2
BL 4407	3957.1	3021.5	2551.0	23.6	15.6	35.5
BL 4669	4612.8	3521	2216.7	23.7	37.0	51.9
BL 4919	6254	3788.5	3084.1	39.4	18.6	50.7
Gautam	3704.8	3129.5	2203.9	15.5	29.6	40.5
NL 1179	3848.8	3204.5	1883.4	16.7	41.2	51.1
NL 1346	5046.8	3476.5	2858.9	31.1	17.8	43.4
NL 1350	4181.4	3567	2825.2	14.7	20.8	32.4
NL 1368	4395.3	4261.5	2410.9	3.0	43.4	45.1
NL 1369	4393.8	3434	2337.8	21.8	31.9	46.8
NL 1376	4097.5	3464.5	3092.6	15.4	10.7	24.5
NL 1381	4427.4	3308.5	2293.9	25.3	30.7	48.2
NL 1384	3611.5	3322.5	2552.2	8.0	23.2	29.3
NL 1386	4202.5	3414	2621.4	18.8	23.2	37.6
NL 1387	4155.5	2513.8	2184.5	39.5	13.1	47.4
NL 1404	4866	3408.5	2584.4	30.0	24.2	46.9
NL 1412	4634.9	3594.5	2751.3	22.4	23.5	40.6
NL 1413	4069.5	3266	2739.7	19.7	16.1	32.7
NL 1417	3805.2	3717	2662.3	2.3	28.4	30.0
NL 1420	3164.4	3130	2373.0	1.1	24.2	25.0
Max	6254.0	4261.5	3322.8	39.4	43.4	51.9
Min	3164.4	2513.8	2184.5	1.1	10.7	13.2
Mean	4262.9	3413.3	2577.5	18.7	24.2	38.7
STD	647.2	350.3	355.3	11.5	9.4	10.6
CV	15.2	10.3	13.8	61.1	38.9	27.4

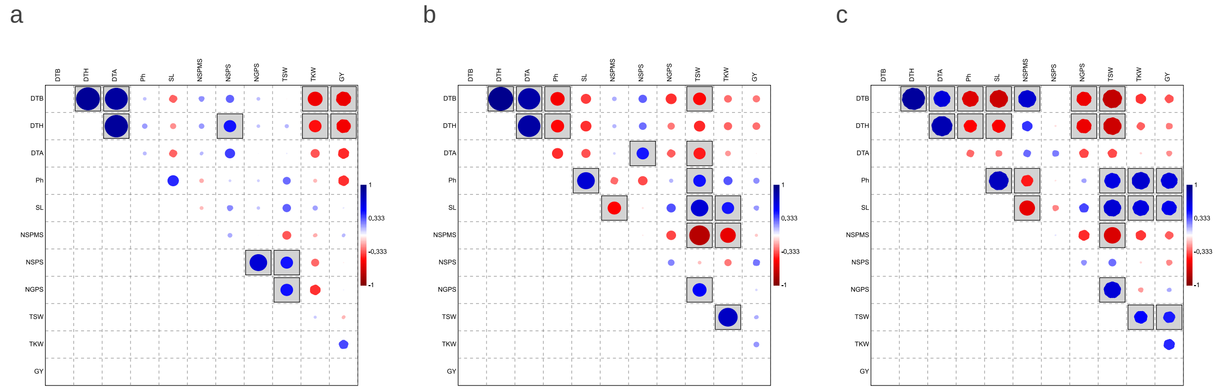

Figure 2. Visualization of correlation among agronomic parameters of wheat under irrigated (2a), heat stress (2b), and heat drought (2c) conditions

Wheat genotypes that are earlier in booting and heading could perform well under irrigated conditions. Earliness in booting and heading prevents wheat to suffer from terminal heat stress of February-March (Figure 1). Late booting and heading genotypes usually get longer vegetative periods for photosynthate accumulation but the temperature above 24 ℃ during critical booting and heading stages hinders the translocation and distribution of photosynthate to the developing spikes, spikelets, and grains resulting in reduced grain yield (Bhandari et al., 2023; Kajal et al., 2015). (Table 6) showed a significant negative correlation between DTB and DTH with TKW. Late booting resulted in shrinkage of developing grain that reduced the seed size and the result was observed with reduced TKW which reduced net yield of wheat genotypes growing under irrigated condition. Several studies have shown that plant height plays a crucial role in determining grain yield (Aisawi et al., 2015; Beche et al., 2014; Bhandari et al., 2023; Chen and Hao, 2015; Deo et al., 2017; Lopes et al., 2012). The taller wheat genotypes face lodging problems during the reproductive phase due to heavy rainfall and high wind velocity that cause difficulty in nutrient uptake, thus reducing grain yield (Khobra et al., 2019). Path analysis showed, plant height (-0.117), days to booting (-0.745), and days to heading (-0.67) have a direct negative effect on the grain yield of wheat (Table 7). The result revealed DTB, DTH, and PH were the as good indicators of the yield, and the selection of the short genotypes which are earlier in DTB and DTH will be high yielding under irrigated condition.

3.4.2. Heat stress condition

The grain yield of wheat was positively associated with plant height. Plant height was significantly negatively correlated with DTB and DTH, whereas it was significantly positively correlated with SL and TSW (Table 6). The result showed that the production of wheat under heat stress conditions is preliminarily associated with plant height, booting and heading days. Wheat sown lately in the western region of Nepal (December 25th onwards) generally suffers from above optimum temperature during growth, jointing, booting, heading, and grain filling (Kajal et al., 2015). Above optimum temperature (16-22 ℃) during the growth stage of wheat accelerates the growth leading to a shorter vegetative period. Reduced vegetative period lowers net photosynthate accumulation, and biomass production leading to a reduced harvest index (HI) (Kumar, 2016). Lack of optimum photosynthate accumulation results in stunting of the genotypes thus producing shorter tillers. Hence, shorter genotypes generally perform poorly under heat-stress conditions. Path analysis revealed that DTH have a direct negative contribution to the grain yield of wheat. Hence, the study revealed the selection of a high-yielding stress-tolerant genotype can be done with Ph, DTB, and DTH (Table 7). Taller genotypes that are earlier in booting and heading will have higher spike length and spike weight which will be most suitable under heat stressed condition.

The result suggests that breeders should focus on selection based on DTB, DTH, and Ph. The significant positive association across genotypes with early flowering and heading with grain yield of wheat has been extensively used in wheat breeding program (Bhandari et al., 2023; Mondal et al., 2016; Pandey et al., 2015; Yu et al., 2017). A positive gain in wheat breeding on the selection with DTH was observed in Mexico as well (Lopes et al., 2012; Tshikunde et al., 2019). Identification of genotypes that are earlier in booting and heading has been one of the basic objectives of the modern wheat breeding program not only under terminal heat but also under drought-stress conditions (Chen et al., 2016; Mondal et al., 2016; Motzo et al., 2007). The genotypes that are earlier in flowering will achieve earlier maturity which results in positive genetic gain in wheat (Bhandari et al., 2023; Kamran et al., 2013; Motzo et al., 2007).

3.4.3. Heat drought condition

The grain yield of wheat was significantly (p≤0.05) positively correlated with Ph, SL, and TSW (Table 6). Plant height was found to have a significant positive correlation with SL, TSW, and TKW, whereas a significant negative correlation was observed with DTB and DTH (Table 6). Heat drought condition reduces the vegetative growth period of wheat which leads to the shorter height of the genotypes as compared to normal conditions (Christopher et al., 2018).

Table 6. Correlation among agronomic parameters of wheat under irrigated, heat stress, and heat drought conditions

Attributes	Conditions	DTB	DTH	DTA	Ph	SL	NSPMS	SPS	GPS	TSW	TKW	GY
DTB	Irrigated	1										
	HS	1										
	HD	1										
DTH	Irrigated	.899**	1									
	HS	.745**	1									
	HD	.882**	1									
DTA	Irrigated	.765**	.759**									
	HS	.768**	.794**	1								
	HD	.643**	.798**									
Ph	Irrigated	0.157	0.250	0.167								
	HS	-.362*	-.347*	-0.218	1							
	HD	-.629**	-.501*	-.296								
SL	Irrigated	-0.084	0.060	-0.029	.401*							
	HS	-0.301	-0.292	-0.177	.498**	1						
	HD	-.698**	-.520*	-.252	.751**							
SPMS	Irrigated	0.153	0.151	0.035	-0.078	-0.251						
	HS	0.049	0.100	0.090	-0.142	-.423**	1					
	HD	.687**	.399	.292	-.456*	-.585**						
SPS	Irrigated	0.287	.367*	0.301	0.071	.396*	0.079					
	HS	0.173	0.155	0.249	-0.248	0.087	-0.162	1				
	HD	-.010	-.075	.250	-.054	-.236	.050					
GPS	Irrigated	0.249	0.299	0.236	-0.020	0.199	-0.056	.680**				
	HS	-.347*	-0.273	-0.297	0.121	.469**	-0.302	.336*	1			
	HD	-.569**	-.571**	-.361	.183	.373	-.422	.225				
TSW	Irrigated	-0.015	0.110	0.068	0.125	.472**	-.374*	.460**	.558**			
	HS	-.367*	-.399*	-.335*	.402*	.731**	-.619**	0.083	.543**	1		
	HD	-.736**	-.692**	-.355	.615**	.676**	-.642**	.291	.655**			
TKW	Irrigated	-.469**	-.400*	-0.256	-0.230	0.054	-0.188	-0.230	-.355*	0.112		
	HS	-0.301	-0.241	-0.180	0.147	.394*	-.481**	-0.134	-0.002	.626**	1	
	HD	-.400	-.311	-.082	.691**	.624**	-.395	-.081	-.195	.503*		
GY	Irrigated	**-.434****	**-.411****	**-0.302**	**-.411****	**-0.157**	**0.108**	**0.052**	**-0.110**	**-0.251**	**0.132**	
	HS	**-0.068**	**-0.137**	**0.036**	**0.207**	**0.303**	**0.142**	**0.120**	**0.081**	**0.174**	**0.071**	1
	HD	**-.334**	**-.258**	**-.221**	**.638****	**.589****	**-.318**	**-.229**	**.170**	**.450***	**.424**	

Table 7. Path analysis among agronomic parameters of wheat and yield under irrigated, heat stress, and heat drought conditions

Attributes	Conditions	DTB	DTH	DTA	Ph	SL	NSPMS	NSPS	NGPS	NSW	TKW	GY
DTB	**Irrigated**	**-0.745**	0.119	0.080	-0.053	0.009	-0.007	0.142	-0.045	0.005	0.062	**-0.434****
	HS	**0.095**	-0.197	0.161	-0.030	-0.09	0.021	0.03	0.022	-0.059	-0.021	**-0.068**
	HD	**0.592**	-0.342	0.063	-0.135	-0.406	-0.090	-0.001	0.082	-0.015	0.136	**-0.115**
DTH	**Irrigated**	-0.670	**0.132**	0.079	-0.084	-0.006	-0.007	0.182	-0.054	-0.036	0.053	**-0.411****
	HS	0.071	**-0.264**	0.167	-0.028	-0.088	0.043	0.027	0.017	-0.064	-0.017	**-0.137**
	HD	0.300	**0.307**	-0.224	-0.276	-0.161	0.025	0.014	0.070	-0.388	0.074	**-0.258**
DTA	**Irrigated**	-0.570	0.100	**0.104**	-0.056	0.003	-0.002	0.149	-0.043	-0.022	0.034	**-0.302**
	HS	0.073	-0.209	**0.210**	-0.018	-0.053	0.038	0.043	0.019	-0.054	-0.013	**0.036**
	HD	0.218	0.245	**-0.280**	-0.163	-0.078	0.019	-0.047	0.045	-0.199	0.019	**-0.221**
Ph	**Irrigated**	-0.117	0.033	0.017	**-0.336**	-0.041	0.004	0.035	0.004	-0.040	0.031	**-0.411****
	HS	-0.034	0.092	-0.046	**0.082**	0.149	-0.06	-0.043	-0.008	0.065	0.010	**0.207**
	HD	-0.214	-0.154	0.083	**0.551**	0.233	-0.029	0.010	-0.023	0.345	-0.164	**0.638****
SL	**Irrigated**	0.063	0.008	-0.003	-0.135	**-0.102**	0.012	0.196	-0.036	-0.153	-0.007	**-0.157**
	HS	-0.029	0.077	-0.037	0.041	**0.300**	-0.18	0.015	-0.03	0.118	0.028	**0.303**
	HD	-0.237	-0.160	0.071	0.414	**0.310**	-0.037	0.044	-0.046	0.379	-0.148	**0.589****
NSPMS	**Irrigated**	-0.114	0.02	0.004	0.026	0.026	**-0.049**	0.039	0.010	0.121	0.025	**0.108**
	HS	0.005	-0.026	0.019	-0.012	-0.127	**0.426**	-0.028	0.019	-0.100	-0.034	**0.142**
	HD	-0.193	-0.175	0.101	0.101	0.116	**-0.027**	-0.042	-0.123	0.367	0.046	**0.170**
NSPS	**Irrigated**	-0.214	0.048	0.031	-0.024	-0.040	-0.004	**0.496**	-0.123	-0.149	0.031	**0.052**
	HS	0.016	-0.041	0.052	-0.020	0.026	-0.069	**0.173**	-0.021	0.013	-0.009	**0.12**
	HD	-0.003	-0.023	-0.070	-0.030	-0.073	0.003	**-0.187**	-0.028	0.163	0.019	**-0.229**
NGPS	**Irrigated**	-0.186	0.039	0.025	0.007	-0.020	0.003	0.337	**-0.182**	-0.181	0.047	**-0.11**
	HS	-0.033	0.072	-0.062	0.010	0.141	-0.129	0.058	**-0.063**	0.087	0.001	**0.081**
	HD	-0.246	0.188	-0.032	0.078	0.289	0.045	0.008	**-0.197**	0.020	0.058	**0.211**
TSW	**Irrigated**	0.011	0.015	0.007	-0.042	-0.048	0.018	0.228	-0.101	**-0.324**	-0.015	**-0.251**
	HS	-0.035	0.105	-0.070	0.033	0.219	-0.264	0.014	-0.034	**0.161**	0.044	**0.174**
	HD	-0.250	-0.213	0.099	0.339	0.210	-0.041	-0.055	-0.081	**0.561**	-0.120	**0.450***
TKW	**Irrigated**	0.349	-0.053	-0.027	0.077	-0.006	0.009	-0.114	0.064	-0.036	**-0.133**	**0.132**
	HS	-0.029	0.064	-0.038	0.012	0.118	-0.205	-0.023	0.001	0.101	**0.071**	**0.071**
	HD	-0.136	-0.096	0.023	0.381	0.193	-0.025	0.015	0.024	0.282	**-0.238**	**0.424**

The residual value for path analysis under irrigated, heat stress (HS), and heat drought (HD) conditions were 0.58, 0.77, and 0.76, respectively.

Plant height is associated with total biomass accumulation in wheat which suggests the genotypes with higher height generally have higher photosynthate accumulated hence, the taller genotypes perform better under heat drought conditions. An increase in plant height promotes spike growth leading to longer spikes, a higher number of grains per spike, and increases the grain yield of wheat. Since, plant height is directly associated with phenological traits specially DTB and DTH, plant breeders should focus on earliness in booting and heading as well. Path analysis revealed that plant height and spike length had a direct positive effect on the grain yield of wheat whereas days to heading and number of spikes per meter square has a direct negative effect on the yield of wheat (Table 7). The results suggested the selection of genotype can be done based on plant height, spike length, and days to heading. The taller genotype that are earlier in heading will have a longer spike length and will yield more under heat drought condition.

3.5. Principal component analysis

Principal component analysis extracted three components for irrigated and heat drought conditions whereas four components for heat stress conditions. The first three PCs contributed about 70.04%, and 72.77% of the total variation under irrigated and heat-drought conditions, respectively. Whereas the first four PCs responsible for 83.04% of the total variation under heat stress conditions (Table 8).

Most of the variation in the data was explained by PC1 and PC2 under all tested conditions. PC1 and PC2 explained a cumulative of 55.76%, 60.74%, and 60.17% of the total variation under irrigated, heat stress, and heat drought condition, respectively. Under Irrigated condition, PC1 showed a negative correlation whereas PC2 showed a positive correlation with GY. The PC1 and PC2 showed a positive correlation with GY under HS and HD conditions. Hence, the genotype with a lower PC1 score and higher PC2 score would yield higher under irrigated condition. Whereas, the genotype with higher PC1 and PC2 scores would yield more under heat-stress and heat-drought conditions (Table 8).

The correlation among the morphological trait studied under all tested conditions was presented on the PCA biplot using vectors (Figure 3). The cosine angle of the vectors was used to interpret the strength of correlation among the traits (Bhandari et al., 2023). The vector angle among two traits close to zero represents a perfect positive correlation whereas the vector angle close to 180 degree represents a perfect negative correlation. The vector angle equal to 90 degrees represents no correlation among the traits. Based on the PCA biplot, GY was positively correlated with TKW whereas negatively correlated with DTB, DTH, and DTA under irrigated condition. TKW, NSW, NGPS, and SL showed a positive correlation with GY whereas NSPMS showed a negative correlation with GY under the HS condition. Similarly, Ph, SL, and TKW showed a positive correlation with GY whereas DTB, DTH, and NSPMS showed a negative correlation with GY under the HD condition (Figure 3).

Based on the PCA biplot BL 4919 (4) and NL 1350 (8) were the highest-yielding wheat genotype under irrigated condition. Whereas, NL 1369 (10) and NL 1417 (19) had the best performance under a heat stress condition. NL 1350 (8) and Bhrikuti (1) were the most adaptive wheat genotypes under the heat drought condition (Figure 3).

3.6. Cluster analysis

Based on correlation, path, and principal component analysis, DTB, DTH, DTA, and TKW were selected for clustering of genotypes under irrigated condition. Similarly, NSPMS, SL, NGPS, TSW, and TKW were selected under heat stress while NSPMS, Ph, SL, TSW, and TKW were selected under heat drought condition. The ward's method based classical clustering of elite wheat genotypes under tested conditions is presented on (Figure 4).

Four classical clusters were formed under across all tested conditions. The mean performance of clusters showed, a general trend of yield reduction from cluster A to D across all tested conditions with increase in DTB, DTH, and DTA (Table 9). Hence, DTB, DTH, DTA can be considered as key traits for selection of high yielding genotypes across all tested conditions. Similarly, selection based on TKW can be employed under irrigated condition (homogenous trend) (Table 9). Under heat stress condition, selection based on NGPS, TSW and TKW can be employed (homogenous trend) while under heat drought condition selection could be employed based on Ph, SL, TSW, TKW (homogenous trend) (Table 9). Selection via plant height becomes more crucial as the severity of temperature stress rises as longer heights are often associated with higher biomass accumulation and cooler canopy temperatures (Bhandari et al., 2023; Cossani and Reynolds, 2015).

3.7. Trait-based selection

From correlation, path, and principal component analysis, phenological traits especially days to booting and days to heading were found the most important trait across all tested wheat growing conditions. More the earliness in attaining these stages, the more the yield across all environmental conditions. The result showed that plant height can also act as a crucial trait for stress breeding. The dwarf genotypes are suitable for irrigated conditions whereas the tall genotypes are for both heat stress and heat drought condition. The descriptive statistics showed Ph decreases under stress conditions. Hence, the genotype with a lower reduction of Ph will have a lower GY reduction under stress condition. Similarly, selection via TKW, TSW also helps for the selection of high yielding genotypes across all tested conditions.

Table 8. Eigen value (EV), percentage variation explained (PV), cumulative percentage variation (CPV), and correlation among principal components (PC1-PC4) with agronomic parameters of wheat genotypes under irrigated heat stress, and heat drought condition

		EV	PV	CPV	DTB	DTH	DTA	Ph	SL	NSPMS	NSPS	NGPS	NSW	TKW	GY
Irrigated	**PC 1**	3.87	35.17	35.17	0.470	0.479	0.436	0.139	-0.091	0.096	0.285	0.168	0.099	-0.326	-0.312
	PC 2	2.27	20.59	55.76	-0.179	-0.076	-0.152	0.301	0.459	-0.238	0.362	0.415	0.526	0.035	0.012
	PC 3	1.57	14.28	70.04	-0.037	-0.051	-0.063	-0.464	-0.148	0.420	0.388	0.424	-0.055	-0.154	0.470
Heat stress	**PC 1**	4.74	43.08	43.08	-0.395	-0.353	-0.353	0.322	0.346	-0.260	-0.099	0.223	0.387	0.283	0.123
	PC 2	1.94	17.66	60.74	0.280	0.355	0.349	-0.092	0.152	-0.484	0.431	0.171	0.306	0.272	0.159
	PC 3	1.38	12.52	73.27	0.202	0.185	0.202	0.294	0.165	-0.120	-0.551	-0.516	0.058	0.355	-0.239
	PC 4	1.08	9.78	83.04	-0.050	-0.092	0.144	0.198	0.041	0.199	0.132	-0.376	-0.172	0.121	0.828
Heat drought	**PC 1**	5.01	45.57	45.57	-0.408	-0.387	-0.307	0.294	0.333	-0.244	-0.047	0.258	0.348	0.284	0.251
	PC 2	1.61	14.60	60.17	0.077	0.127	0.388	0.041	-0.016	-0.039	0.747	0.274	0.420	-0.075	0.094
	PC 3	1.39	12.61	72.77	0.171	0.313	0.259	0.320	0.031	-0.092	-0.100	-0.478	0.035	0.398	0.544

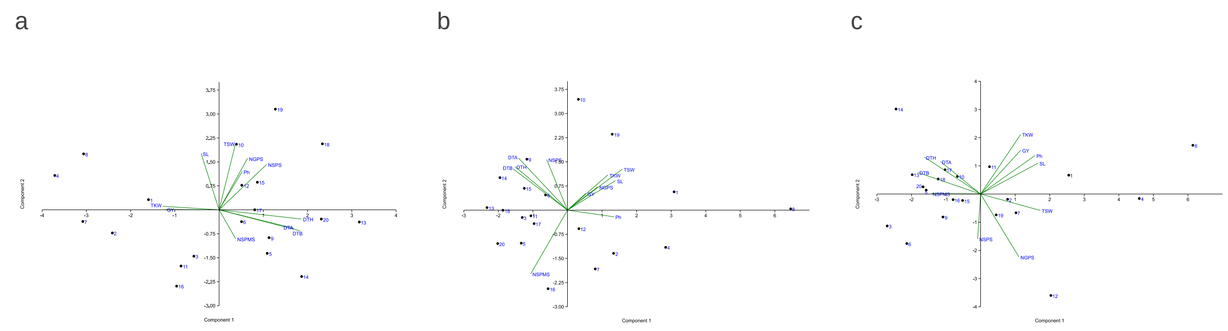

Figure 3. Principal component analysis (PCA) biplot showing eleven morphological traits and twenty wheat genotypes under irrigated (3a), heat stress (3b), and heat drought (3c) conditions

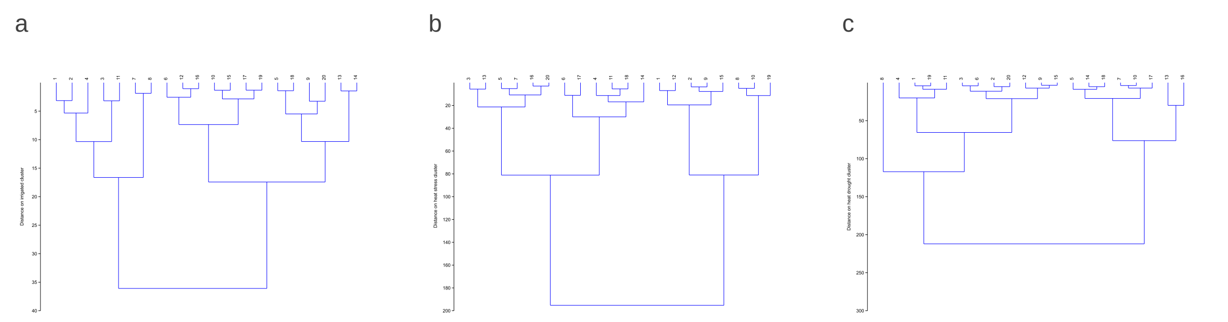

Figure 4. Classical cluster analysis based on selected traits from correlation, path analysis and principal component analysis

Table 9. Mean performance of genotypic clusters under irrigated, heat stress, and heat drought conditions

		No. of genotypes	DTB	DTH	DTA	Ph (cm)	SL (cm)	NSPMS	NSPS	NGPS	TSW (g)	TKW (g)	GY (kg ha-1)
Irrigated	A	5	75	84	89	95.9	10.3	353.5	17.4	43.1	22.4	47.1	4549.9
	B	2	70	80	85	100.9	11.0	352.8	16.8	46.7	22.0	39.7	4614.1
	C	7	78	87	91	101.3	10.2	339.4	18.4	48.0	24.5	38.4	4304.5
	D	6	83	90	93	98.9	10.3	385.9	18.7	47.6	22.2	35.3	3858.0
Heat stress	A	3	67	72	75	98.5	11.5	264.7	17.7	49.3	27.4	40.0	3572.7
	B	5	67	72	75	92.6	10.8	320.8	17.7	46.1	21.4	34.2	3299.8
	C	6	68	73	75	93.1	9.8	350.8	17.5	42.8	20.4	34.9	3455.3
	D	6	68	72	75	92.8	9.8	392.4	17.5	42.9	18.4	32.3	3337.3
Heat drought	A	1	63	70	74	110.1	13.6	231.6	17.0	47.6	26.0	45.9	2825.2
	B	11	67	72	75	97.6	10.5	331.6	18.8	48.4	22.0	35.9	2582.2
	C	6	69	73	75	99.0	10.3	382.4	18.7	43.3	20.6	38.2	2585.5
	D	2	68	73	75	99.1	10.5	437.0	18.4	44.1	18.8	34.7	2568.3

4. Discussion

Recently, the incorporation of dwarfism genes such as Rht5 in combination with photoperiod insensitive gene Ppd-D1 was found to shorten the duration of the reproductive phase and facilitate early flowering of wheat (Chen et al., 2016, 2018a, 2018b; Du et al., 2018). Here, the short height accounts for a reduction in lodging problems in wheat (Berry et al., 2015; Bhandari et al., 2023). Integration of height-reducing genes such as Rht4, Rht5, Rht11, Rht12, and Rht24 were found to improve lodging resistance under irrigated environments (Beche et al., 2014; Berry et al., 2015; Divashuk et al., 2013; Gao et al., 2017). Hence, work is continuously being performed for the incorporation of dwarfism genes Rht1 (Rht-B1b), Rht1 (Rht-B1b), Rht2 (Rht-D1b), Rht-D1c, and Rht8 (Chairi et al., 2018; Zhang et al., 2016) to reduce the plant height of wheat to increase the partitioning of the assimilate to the spike (Grover et al., 2018).

CIMMYT has been developing high-yielding heat stress tolerance genotypes to diverse environmental conditions via the selection of early maturing genotypes along with the incorporation of dwarfing genes (Bhandari et al., 2023; Chen et al., 2016; Mondal et al., 2016). A significant negative correlation across DTA and grain yield potential of bread wheat has been reported that suggested the importance of phenology in the wheat improvement program (Bhandari et al., 2021; Guzmán et al., 2017; Mondal et al., 2016; Poudel et al., 2023). The genotypes which are earlier in heading, flowering with faster growth rate can accumulate sufficient biomass in a short period and can have high yield potential (Bhandari et al., 2023; Tshikunde et al., 2019). The wheat improvement program has been preliminary focused on the promotion of early maturing lines. The genetic gain obtained in wheat cultivars through early maturity varieties has become a significant contributor to high yield of wheat (Giunta et al., 2019; Tshikunde et al., 2019). The genotypes that are earlier in the booting and heading stages would not experience upcoming terminal heat stress during pollen maturation, pollen viability, pollination, and stigmata responsiveness. The report from Mexico showed positive genetic gain with the genotypes with higher plant height under low-yielding stress conditions (Tshikunde et al., 2019; Zhang et al., 2016). A dwarf wheat variety may be beneficial for the plant's root and shoot regions to store more photosynthates (Bhandari et al., 2023; Paudel et al., 2023). The plant with a higher shoot system will have a lower canopy temperature due to the high biomass on the field. Research outcomes showed a significant negative correlation between canopy temperature and grain yield of bread wheat(Lopes et al., 2012). The taller plant height is accompanied by lower canopy temperature. The genotype which is taller in length is hence, able to tolerate the extreme heat of the environment compared to shorter genotypes. Since increased plant height has a strong positive correlation with spike length and weight, which further increase yield in heat-stressed conditions.

Cumulative heat and drought stress were the most damaging stress environments. Wheat experiencing these stresses has a severe impact on various yield attributes. The findings suggest plant breeders should select taller genotypes with earlier heading under stressful environments. To avoid terminal heat stress, earliness in wheat plays a very significant role (Bhandari et al., 2023; Nyaupane et al., 2023). Since the addition of drought aggravates the canopy temperature and promotes heat stress. To reduce canopy temperature, taller genotypes would be effective. Research has shown, the taller plants are accomplished with lower canopy temperatures. Furthermore, a significant negative correlation across canopy temperature and grain yield occurs, which suggests taller genotypes would give the most profitable yield across a heat drought environment (Bhandari et al., 2023; Sharma et al., 2023; Timalsina et al., 2023). Canopy temperature is crucial in wheat production, cooler canopy temperature during the mid-grain filling period leads to higher yield and drought tolerance (Gao et al., 2017; Gupta et al., 2022; Lopes et al., 2012; Lopes and Reynolds, 2010).

From the research, DTB and DTH have a direct negative impact on yield of wheat. This would aid the genotype in preventing losses due to decreased pollen fertility and viability as well as decreased stigmatic receptivity, which would ultimately result in decreased numbers of viable florets per spike, grains per spike, and thousand-grain weight under a heat drought environment. For the breeding of winter wheat in a heat-drought environment, all those variables would be crucial. The significant positive association and direct effect of height on GY have been extensively reported by many researchers. CIMMYT has been working on the development of tall genotypes to cultivate under heat-stressed and drought environments (Chen et al., 2016; Mondal et al., 2016; Motzo et al., 2007). A genotype that is higher in plant height might be helpful for more photosynthates accumulation at the root and shoot portion of the plant. Since height had an indirect effect on GY via DTH, the selection of genotypes with the integration of data from phenology is essential for the effective selection of genotypes under a heat-drought environment.

5. Conclusion

The fluctuation in grain yield is primarily due to the influence of the environment. The yield and its attributing parameters express and associate with one another differently across different environments. Yield being the major parameter for any breeder, the study of the direct and indirect effect of yield-attributing parameters is crucial for effective breeding. The experiment was conducted to evaluate the direct and indirect association among quantitative traits of wheat. The results revealed that days to booting (DTB), days to heading (DTH) and plant height (Ph) were the most important yield-determining traits of wheat across all conditions. Days to heading (DTH) and days to booting (DTB) had a significant negative impact on the grain yield of wheat across all tested condition. Plant height was found to be significantly ($p \leq 0.05$) negatively associated with GY under irrigated conditions, but a significantly positive association was observed under heat-stressed (HS) and heat-drought conditions (HD). To effectively select high-yielding genotypes, the trait-based selection method is beneficial. Genotypes with short heights that are earlier in booting (DTB) and days to heading (DTH) should be promoted under high-yielding irrigation condition, whereas the taller genotypes that are earlier in days to booting (DTB) and days to heading (DTH) should be promoted under low-yielding heat stress and heat drought conditions. Based on selected traits, BL 4919 and NL 1350 were selected as high yielding genotypes under irrigated, NL 1369 and NL 1417 under heat stress and NL 1350 and Bhrikuti under the heat drought condition. These genotypes could further be evaluated to release as a potential climate resilient variety.

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Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

Abhinandan, K., Skori, L., Stanic, M., Hickerson, N.M.N., Jamshed, M., Samuel, M.A., 2018. Abiotic stress signaling in wheat – An inclusive overview of hormonal interactions during abiotic stress responses in wheat. Front. Plant Sci. 9, 1–25. https://doi.org/10.3389/fpls.2018.00734

Aisawi, K.A.B., Reynolds, M.P., Singh, R.P., Foulkes, M.J., 2015. The physiological basis of the genetic progress in yield potential of CIMMYT spring wheat cultivars from 1966 to 2009. Crop Sci. 55, 1749–1764. https://doi.org/10.2135/CROPSCI2014.09.0601

Beche, E., Benin, G., da Silva, C.L., Munaro, L.B., Marchese, J.A., 2014. Genetic gain in yield and changes associated with physiological traits in Brazilian wheat during the 20th century. Eur. J. Agron. 61, 49–59. https://doi.org/10.1016/J.EJA.2014.08.005

Berry, P.M., Kendall, S., Rutterford, Z., Orford, S., Griffiths, S., 2015. Historical analysis of the effects of breeding on the height of winter wheat (Triticum aestivum) and consequences for lodging. Euphytica 203, 375–383. https://doi.org/10.1007/S10681-014-1286-Y

Bhandari, R., Gnawali, S., Nyaupane, S., Kharel, S., Poudel, M., Panth, P., 2021. EFFECT OF DROUGHT & IRRIGATED ENVIRONMENTAL CONDITION ON YIELD & YIELD ATTRIBUTING CHARACTERISTIC OF BREAD WHEAT-A REVIEW. Artic. J. Sci. Food Agric. 2, 59–62. https://doi.org/10.26480/rfna.02.2021.59.62

Bhandari, R.K., Nyaupane, S., Poudel, M.R., 2023. Expression and association of quantitative traits of wheat (Triticum aestivum L .) genotypes under different wheat growing environments. Cogent Food Agric. 9, 1–21. https://doi.org/10.1080/23311932.2023.2288394

Bhanu, A.N., 2018. Genetic Variability, Heritability and Correlation Study of Physiological and Yield Traits in Relation to Heat Tolerance in Wheat (Triticum aestivum L.). Biomed. J. Sci. Tech. Res. 2. https://doi.org/10.26717/bjstr.2017.01.000636

Bustos, D. V., Hasan, A.K., Reynolds, M.P., Calderini, D.F., 2013. Combining high grain number and weight through a DH-population to improve grain yield potential of wheat in high-yielding environments. F. Crop. Res. 145, 106–115. https://doi.org/10.1016/J.FCR.2013.01.015

Chairi, F., Vergara-Diaz, O., Vatter, T., Aparicio, N., Nieto-Taladriz, M.T., Kefauver, S.C., Bort, J., Serret, M.D., Araus, J.L., 2018. Post-green revolution genetic advance in durum wheat: The case of Spain. F. Crop. Res. 228, 158–169. https://doi.org/10.1016/J.FCR.2018.09.003

Chatrath, R., Mishra, B., Ortiz Ferrara, G., Singh, S.K., Joshi, A.K., 2007. Challenges to wheat production in South Asia. Euphytica 157, 447–456. https://doi.org/10.1007/S10681-007-9515-2

Chen, H., Moakhar, N.P., Iqbal, M., Pozniak, C., Hucl, P., Spaner, D., 2016. Genetic variation for flowering time and height reducing genes and important traits in western Canadian spring wheat. Euphytica 208, 377–390. https://doi.org/10.1007/S10681-015-1615-9

Chen, L., Du, Y., Lu, Q., Chen, H., Meng, R., Cui, C., Lu, S., Yang, Y., Chai, Y., Li, J., Liu, L., Qi, X., Li, H., Mishina, K., Yu, F., Hu, Y.G., 2018a. The photoperiod-insensitive allele Ppd-D1a promotes earlier flowering in Rht12 dwarf plants of bread wheat. Front. Plant Sci. 871. https://doi.org/10.3389/FPLS.2018.01312

Chen, L., Yang, Y., Cui, C., Lu, S., Lu, Q., Du, Y., Su, R., Chai, Y., Li, H., Chen, F., Yu, F., Hu, Y.G., 2018b. Effects of Vrn-B1 and Ppd-D1 on developmental and agronomic traits in Rht5 dwarf plants of bread wheat. F. Crop. Res. 219, 24–32. https://doi.org/10.1016/J.FCR.2018.01.022

Chen, X., Hao, M.D., 2015. Low contribution of photosynthesis and water-use efficiency to improvement of grain yield in Chinese wheat. Photosynthetica 53, 519–526. https://doi.org/10.1007/S11099-015-0147-9

Chen, X., Min, D., Yasir, T.A., Hu, Y.G., 2012. Evaluation of 14 morphological, yield-related and physiological traits as indicators of drought tolerance in Chinese winter bread wheat revealed by analysis of the membership function value of drought tolerance (MFVD). F. Crop. Res. 137, 195–201. https://doi.org/10.1016/j.fcr.2012.09.008

Christopher, M., Chenu, K., Jennings, R., Fletcher, S., Butler, D., Borrell, A., Christopher, J., 2018. QTL for stay-green traits in wheat in well-watered and water-limited environments. F. Crop. Res. 217, 32–44. https://doi.org/10.1016/J.FCR.2017.11.003

Cossani, C.M., Reynolds, M.P., 2015. Heat stress adaptation in elite lines derived from synthetic hexaploid wheat. Crop Sci. 55, 2719–2735. https://doi.org/10.2135/CROPSCI2015.02.0092

Crespo-Herrera, L.A., Crossa, J., Huerta-Espino, J., Vargas, M., Mondal, S., Velu, G., Payne, T.S., Braun, H., Singh, R.P., 2018. Genetic gains for grain yield in cimmyt's semi-arid wheat yield trials grown in suboptimal environments. Crop Sci. 58, 1890–1898. https://doi.org/10.2135/CROPSCI2018.01.0017

De Vita, P., Nicosia, O.L.D., Nigro, F., Platani, C., Riefolo, C., Di Fonzo, N., Cattivelli, L., 2007. Breeding progress in morpho-physiological, agronomical and qualitative traits of durum wheat cultivars released in Italy during the 20th century. Eur. J. Agron. 26, 39–53. https://doi.org/10.1016/J.EJA.2006.08.009

Deo, K., Singh, A., Mishra, S.R., Singh, A.K., Mishra, A.N., 2017. Water requirement of wheat crop for optimum production using CROPWAT model. ~ 338 ~ J. Med. Plants Stud. 5, 338–342.

Divashuk, M.G., Bespalova, L.A., Vasilyev, A. V., Fesenko, I.A., Puzyrnaya, O.Y., Karlov, G.I., 2013. Reduced height genes and their importance in winter wheat cultivars grown in southern Russia. Euphytica 190, 137–144. https://doi.org/10.1007/S10681-012-0789-7

Du, Y., Chen, L., Wang, Y., Yang, Z., Saeed, I., Daoura, B.G., Hu, Y.G., 2018. The combination of dwarfing genes Rht4 and Rht8 reduced plant height, improved yield traits of rainfed bread wheat (Triticum aestivum L.). F. Crop. Res. 215, 149–155. https://doi.org/10.1016/J.FCR.2017.10.015

Fahad, S., Bajwa, A.A., Nazir, U., Anjum, S.A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S., Ihsan, M.Z., Alharby, H., Wu, C., Wang, D., Huang, J., 2017. Crop production under drought and heat stress: Plant responses and management options. Front. Plant Sci. 8, 1–16. https://doi.org/10.3389/fpls.2017.01147

Gao, F., Ma, D., Yin, G., Rasheed, A., Dong, Y., Xiao, Y., Xia, X., Wu, X., He, Z., 2017. Genetic progress in grain yield and physiological traits in Chinese wheat cultivars of southern Yellow and Huai Valley since 1950. Crop Sci. 57, 760–773. https://doi.org/10.2135/CROPSCI2016.05.0362

Giunta, F., Pruneddu, G., Motzo, R., 2019. Grain yield and grain protein of old and modern durum wheat cultivars grown under different cropping systems. F. Crop. Res. 230, 107–120. https://doi.org/10.1016/J.FCR.2018.10.012

Grover, G., Sharma, A., Gill, H.S., Srivastava, P., Bains, N.S., 2018. Rht8 gene as an alternate dwarfing gene in elite Indian spring wheat cultivars. PLoS One 13. https://doi.org/10.1371/JOURNAL.PONE.0199330

Gupta, S., Yadav, B., Timalsina, B., Ganesh, G.C., Bhuj, N., Roka, P., Bhandari, R., 2022. Reviews In Food And Agriculture (RFNA) PHYSIOLOGICAL , MORPHOLOGICAL & BIOCHEMICAL RESPONSE OF WHEAT (TRITICUM AESTIVUM) AGAINST HEAT & DROUGHT STRESS AND THE TOLERANCE MECHANISM - A REVIEW 3, 43–47. https://doi.org/10.26480/rfna.01.2022.43.47

Guzmán, C., Autrique, E., Mondal, S., Huerta-Espino, J., Singh, R.P., Vargas, M., Crossa, J., Amaya, A., Peña, R.J., 2017. Genetic improvement of grain quality traits for CIMMYT semi-dwarf spring bread wheat varieties developed during 1965–2015: 50 years of breeding. F. Crop. Res. 210, 192–196. https://doi.org/10.1016/J.FCR.2017.06.002

Joudi, M., Ahmadi, A., Mohammadi, V., Abbasi, A., Mohammadi, H., 2014. Genetic changes in agronomic and phenologic traits of Iranian wheat cultivars grown in different environmental conditions. Euphytica 196, 237–249. https://doi.org/10.1007/S10681-013-1027-7

Kajal, M., Yadav, V.K., Chhokar, R.S., Sharma, R.K., 2015. Management practices to mitigate the impact of high temperature on wheat. J. Wheat Res. 7, 1–12.

Kamran, A., Randhawa, H.S., Pozniak, C., Spaner, D., 2013. Phenotypic effects of the flowering gene complex in Canadian spring wheat germplasm. Crop Sci. 53, 84–94. https://doi.org/10.2135/CROPSCI2012.05.0313

Khan, M., Dar, A., 2010. Correlation and path coefficient analysis of some quantitative traits in wheat. African Crop Sci. J. 18. https://doi.org/10.4314/acsj.v18i1.54188

Khobra, R., Sareen, S., Meena, B.K., Kumar, A., Tiwari, V., Singh, G.P., 2019. Exploring the traits for lodging tolerance in wheat genotypes: a review. Physiol. Mol. Biol. Plants 25, 589–600. https://doi.org/10.1007/s12298-018-0629-x

Kumar, N., 2016. Impact of Heat Stress on Yield and Yield Attributing Traits in Wheat (Triticum aestivum L.) Lines during Grain Growth Development. Int. J. Pure Appl. Biosci. 4, 179–184. https://doi.org/10.18782/2320-7051.2316

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529, 84–87. https://doi.org/10.1038/nature16467

Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D.B., Martre, P., Ruane, A.C., Wallach, D., Jones, J.W., Rosenzweig, C., Aggarwal, P.K., Alderman, P.D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng, D., De Sanctis, G., Doltra, J., Fereres, E., Folberth, C., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Kimball, B.A., Koehler, A.K., Kumar, S.N., Nendel, C., O'Leary, G.J., Olesen, J.E., Ottman, M.J., Palosuo, T., Prasad, P.V.V., Priesack, E., Pugh, T.A.M., Reynolds, M., Rezaei, E.E., Rötter, R.P., Schmid, E., Semenov, M.A., Shcherbak, I., Stehfest, E., Stöckle, C.O., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wall, G.W., Wang, E., White, J.W., Wolf, J., Zhao, Z., Zhu, Y., 2016. Similar estimates of temperature impacts on global wheat yield by three independent methods. Nat. Clim. Chang. 6, 1130–1136. https://doi.org/10.1038/nclimate3115

Liu, H., Searle, I.R., Mather, D.E., Able, A.J., Able, J.A., 2015. Morphological, physiological and yield responses of durum wheat to pre-anthesis water-deficit stress are genotype-dependent. Crop Pasture Sci. 66, 1024–1038. https://doi.org/10.1071/CP15013

Lopes, M.S., Reynolds, M.P., 2010. Partitioning of assimilates to deeper roots is associated with cooler canopies and increased yield under drought in wheat. Funct. Plant Biol. 37, 147–156. https://doi.org/10.1071/FP09121

Lopes, M.S., Reynolds, M.P., Manes, Y., Singh, R.P., Crossa, J., Braun, H.J., 2012. Genetic yield gains and changes in associated traits of CIMMYT spring bread wheat in a "Historic" set representing 30 years of breeding. Crop Sci. 52, 1123–1131. https://doi.org/10.2135/CROPSCI2011.09.0467

Manès, Y., Gomez, H.F., Puhl, L., Reynolds, M., Braun, H.J., Trethowan, R., 2012. Genetic yield gains of the CIMMYT International semi-arid wheat yield trials from 1994 to 2010. Crop Sci. 52, 1543–1552. https://doi.org/10.2135/CROPSCI2011.10.0574

MOALD, 2020. Statistical Information in Nepalese Agriculture. Minist. Agric. Livest. 290.

Mondal, S., Singh, R.P., Mason, E.R., Huerta-Espino, J., Autrique, E., Joshi, A.K., 2016. Grain yield, adaptation and progress in breeding for early-maturing and heat-tolerant wheat lines in South Asia. F. Crop. Res. 192, 78–85. https://doi.org/10.1016/j.fcr.2016.04.017

Motzo, R., Agronomy, F.G.-E. journal of, 2007, U., 2007. The effect of breeding on the phenology of Italian durum wheats: From landraces to modern cultivars. Elsevier.

Mwadzingeni, L., Shimelis, H., Rees, D.J.G., Tsilo, T.J., 2017. Genome-wide association analysis of agronomic traits in wheat under drought-stressed and non-stressed conditions. PLoS One 12. https://doi.org/10.1371/journal.pone.0171692

Nyaupane, S., Bhandari, R., Poudel, M.R., 2023. Evaluation of wheat genotypes using stress tolerance indices under irrigated and drought at late sown condition. J. Innov. Agric. 10, 37–47. https://doi.org/10.37446/jinagri/rsa/10.3.2023.37-47

Pandey, G.C., Mamrutha, H.M., Tiwari, R., Sareen, S., Bhatia, S., Siwach, P., Tiwari, V., Sharma, I., 2015. Physiological traits associated with heat tolerance in bread wheat (Triticum aestivum L.). Physiol. Mol. Biol. Plants 21, 93–99. https://doi.org/10.1007/S12298-014-0267-X

Paudel, H., Bhandari, R., Dhakal, A., Nyaupane, S., Panthi, B., Poudel, M.R., 2023. RESPONSE OF WHEAT TO DIFFERENT ABIOTIC STRESS CONDITIONS : A RESPONSE OF WHEAT TO DIFFERENT ABIOTIC STRESS CONDITIONS : A REVIEW. https://doi.org/10.26480/gws.01.2023.27.31

Poudel, M.R., Ghimire, S., Prasad, P., Dhakal, K.H., Thapa, D.B., Poudel, H.K., 2020. Evaluation of Wheat Genotypes under Irrigated,Heat Stress and Drought Conditions. J. Biol. Today's World 9, 212. https://doi.org/10.35248/2322-3308.20.9.212

Poudel, M.R., Neupane, M.P., Panthi, B., Bhandari, R., Nyaupane, S., Dhakal, A., Paudel, H., 2023. Yield performance and stress tolerance indices of wheat genotypes under irrigated and rainfed condition. J. Innov. Agric. 10, 10–20.

Rahaie, M., Xue, G.-P., M., P., 2013. The Role of Transcription Factors in Wheat Under Different Abiotic Stresses. Abiotic Stress - Plant Responses Appl. Agric. https://doi.org/10.5772/54795

Sharma, R.C., Crossa, J., Velu, G., Huerta-Espino, J., Vargas, M., Payne, T.S., Singh, R.P., 2012. Genetic Gains for Grain Yield in CIMMYT Spring Bread Wheat across International Environments. Crop Sci. 52, 1522–1533. https://doi.org/10.2135/CROPSCI2011.12.0634

Sharma, S., Chaudhary, E., Gautam, P., Poudel, R., Sapkota, S., Ghimire, S., Timalsina, B., Roka, P., Bhattarai, K., Pariyar, M., Neupane, K., Aryal, A., G.C, G., Poudel, M.R., Bhandari, R., 2023. Identification of Heat Stress Tolerant Wheat Genotype Using Stress Tolerance Indices. J. Soil, Plant Environ. 2, 16–27. https://doi.org/10.56946/jspae.v2i2.185

Shewry, P.R., Hey, S.J., 2015. The contribution of wheat to human diet and health. Food Energy Secur. 4, 178–202. https://doi.org/10.1002/FES3.64

Shiferaw, B., Smale, M., Braun, H.J., Duveiller, E., Reynolds, M., Muricho, G., 2013. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. Food Secur. 5, 291–317. https://doi.org/10.1007/S12571-013-0263-Y

Timalsina, B., Ghimire, S., Roka, P., Poudel, R., Sapkota, S., Aryal, A., Ganesh, G.C., Neupane, K., Gautam, P., Pariyar, M.K., Sharma, S., Chaudhary, E., Poudel, M.R., Bhandari, R., 2023. AMMI and GGE biplot analysis of yield performance of wheat genotypes under irrigated, heat stress and heat drought environments. J. Agric. Appl. Biol. 4, 191–201. https://doi.org/10.11594/jaab.04.02.09

Tshikunde, N.M., Mashilo, J., Shimelis, H., Odindo, A., 2019. Agronomic and Physiological Traits, and Associated Quantitative Trait Loci (QTL) Affecting Yield Response in Wheat (Triticum aestivum L.): A Review. Front. Plant Sci. 10, 1428. https://doi.org/10.3389/FPLS.2019.01428/XML/NLM

Upadhyay, K., 2020. Correlation and path coefficient analysis among yield and yield attributing traits of wheat (Triticum aestivum L.) genotypes. Arch. Agric. Environ. Sci. 5, 196–199. https://doi.org/10.26832/24566632.2020.0502017

Upadhyaya, N., Bhandari, K., 2022. Assessment of different genotypes of wheat under late sowing condition. Heliyon 8, e08726. https://doi.org/10.1016/J.HELIYON.2022.E08726

Wieser, H., Koehler, P., Scherf, K.A., 2020. The Two Faces of Wheat. Front. Nutr. 7. https://doi.org/10.3389/fnut.2020.517313

Yu, T.F., Xu, Z.S., Guo, J.K., Wang, Y.X., Abernathy, B., Fu, J.D., Chen, X., Zhou, Y. Bin, Chen, M., Ye, X.G., Ma, Y.Z., 2017. Improved drought tolerance in wheat plants overexpressing a synthetic bacterial cold shock protein gene SeCspA. Sci. Rep. 7, 1–14. https://doi.org/10.1038/srep44050

Zhang, Y., Xu, W., Wang, H., Dong, H., Qi, X., Zhao, M., Fang, Y., Gao, C., Hu, L., 2016. Progress in genetic improvement of grain yield and related physiological traits of Chinese wheat in Henan Province. F. Crop. Res. 199, 117–128. https://doi.org/10.1016/J.FCR.2016.09.022