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RESEARCH ARTICLE

Multivariate analysis of drought stress indices to assess bread wheat (*Triticum aestivum* L.) germplasm under rainfed conditions

Vishnu Kumar*,$, Vikram Singh[1], Arun Gupta, Vikas Gupta amd Gyanendra Pratap Singh$

Abstract

Water stress impacts wheat yields and poses a serious threat to stabilizing the global food supply. In the present investigation, 71 diverse bread wheat germplasm accessions were evaluated at Karnal and Hisar under normal and rainfed (four environments) conditions during *rabi,* 2022-23. The overall pooled grain yield showed a reduction of 15.6% under water stress, while days to heading, tiller count and plant height were reduced by 8.1, 15.5 and 12.5%, respectively. The genotypes, namely K8027, HI1531, PBW175, UAS375, WH1142, HI1612 and K1317 showed higher NDVI values both at heading and grain filling stages under water stress conditions. Grain yield showed positive and significant associations with 1000-grain wt. (r=0.62***) and no. of tillers/m (r=0.53***). In the principal component biplots, 14 drought stress indices were grouped into three clusters. The genotypes K9465, HD2987 and K8027 were the three top rankers for drought susceptibility index; however, they showed yield reduction of 10.4, 5.5 and 17.4% over the best check NIAW3170. Most of the drought stress indices considered only the grain yield reduction as selection criteria; however, the yield potential coupled with drought tolerance is desired to get favourable gene constellations. The drought resistance index (DRI) was highly successful in identifying high-yielding and drought-tolerant genotypes. The genotypes *viz*., HD3171, MP1358, 20th HTWYT-48, 29th SAWYT-316, WAP91 and K1317, appeared to be high-yielding and water stress-tolerant. The traits, such as 1000 grain weight, no. of grains/spike and tiller count, can be targeted as on-farm selection criteria under water stress and to train genomic models.

Keywords: Wheat, water stress, drought stress indices, PCA biplot

Introduction

Wheat is an important cereal crop, occupying 220 m ha of area worldwide, followed by maize (208 m ha) and rice (168.35 m ha). However, in terms of global production, it ranked third (799 m t) after maize (1241.55 m t) and rice (800 m t) with an average productivity of 3.65 t ha^{-1} (FAOSTAT, 2025). Wheat is a staple food crop and caters to the daily dietary needs of 35% of the global population (Allahverdiyev et al. 2025; Sangha et al. 2025). India is the second largest wheat producer and an all-time high wheat production of 117.5 m t has been projected for the year 2024-25. India shares nearly 13.8, 31.4 and 69% of the global, Asian and South Asian wheat production. Global wheat production has witnessed an increase of 36% since 2000. Similarly, Asian, South-Asian and Indian wheat production has also witnessed an increase of 38.3, 45.6 and 45%, respectively. However, the global and Asian wheat acreages showed a marginal increase of 2.45 and 2.38% over the year 2000. In contrast, South-Asian and Indian wheat areas were increased by 11.39 and 14.26%, respectively. In contrast, the Indian population showed an upward growth of 38% during the past 25 years, which mainly depends on wheat for food and protein needs (Mottaleb et al. 2023). Kumar et al. (2025) reported that food demand will rise by 60 to 70% of the present supply by 2050 to feed the global population. Wheat has seen remarkable growth; however, the challenges, like

ICAR-Indian Institute of Wheat & Barley Research, Karnal 132001, Haryana, India

[1]Vikram Singh, Chaudhary Charan Singh Haryana Agricultural University, Hisar 125004, Haryana, India

$Present address: Vishnu Kumar and Gyanendra Pratap Singh, ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi 110012, India

***Corresponding Author:** Vishnu Kumar, ICAR-Indian Institute of Wheat & Barley Research, Karnal 132001, Haryana, India, E-Mail: vishnupbg@gmail.com

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soil health, depleting natural resources, global warming and changed pest and disease dynamics, need to be addressed sustainably (Qian et al. 2025).

The impact of climate change is conspicuous, where effects of drought stress are largely detrimental and can reduce crop yields to the tune of 50% under severe stress conditions (Bapela et al. 2022). Nearly 50% of the global wheat area, including Africa, Australia, regions of China, parts of India and Russia, is largely under rainfed conditions and prone to low wheat yields (Pequeno et al. 2021). Drought impacts crop growth and exerts cytotoxic effects on physiological processes, including photosynthetic rate, stomatal conductance, cell membrane stability, chlorophyll content, etc. (Sairam and Saxena 2000; Zhao et al. 2020; Nyaupane et al. 2024; Priya et al. 2025). The low seedling survivability under water stress is one of the major yield-limiting factors, along with various other factors (Tomar and Kumar 2004). The stake of irrigated land varies, from Africa (4%) of the total cropped area to South Asia (42%). In the Indian scenario, 45% of the net sown crop area is under rainfed conditions. Increasing wheat yields under changing climate and drought stress is challenging as drylands share 47% of the global land and 66% of global wheat area (Mohammadi 2018; Qiu et al. 2022; Mutanda et al. 2025; Arif et al. 2025). The water stress experienced at the post-anthesis, grain filling and terminal stages is the most critical in wheat (Farooq et al. 2014). Under such a situation of scanty irrigation and rainfed agriculture, the challenges are enormous to feed the burgeoning population and stabilize the agricultural food system. Besides improving irrigation facilities, the deployment of water stress resilient wheat genotypes is an economic, viable and eco-friendly solution.

In general, the Indian wheat genotypes, namely, K8027, K9465, HINDI62, HI1500, C306, K1317, NIAW34, NI5439 and PBW175, are considered drought-tolerant and used as one of the parents in the crossing programs. (Subrahmanyam et al. 2006; Kadam et al. 2012; Kumar et al. 2018; Pandey et al. 2023). These genotypes are low-yielding, susceptible to wheat rusts and repeated use in the breeding programs leads to the loss of genetic diversity. The narrow genetic base, poor specific combining ability and low extent of heterosis are other obstacles with the above genotypes in generating stress-tolerant materials (Balla et al. 2025). For instance, the most widely used parent, C306, is a *Ne1* carrier and shows hybrid mortality at the hybrid seedling stage (Vikas et al. 2013; Manoj et al. 2020). Here, the highly diverse nature of the experimental materials, real field conditions and application of 14 drought stress indices gives a comparative advantage over the previous studies. Therefore, the present study was aimed at investigation the response of water stress based on multivariate analysis of drought stress indices to identify high-yielding and drought-tolerant genotypes.

Materials and methods

Planting materials and experimental site

The present study was carried out to assess the effect of water stress on 71 bread wheat (*Triticum aestivum* L.) genotypes grown under four environments (normal and water stress) during *rabi,* 2022-23. The experiments were conducted at Karnal and Hisar locations under rainfed early sown (October 2022: water stress) and irrigated timely sown (November 2022) conditions. An extremely diverse wheat germplasm (71) comprised of registered unique germplasm for water stress (12), released cultivars (30), advance breeding lines (14) and exotic breeding lines selected from CIMMYT yield trials (11), along with four check varieties (C306, DBW110, DBW296 and NIAW3170), was evaluated under rainfed and irrigated conditions. The released cultivars were selected out of a database of nearly 450 released varieties being grown under different agro-ecologies of rainfed and restricted irrigation (water stress), timely sown (high yield potential), late and very late sown (early maturity: escape mechanism) and well reported with drought stress resilience. Similarly, 11 exotic promising lines were selected from the CIMMYT trials 29thSAWYT and 20thHTWYT evaluated during r*abi,* 2021-22, whereas 14 advanced breeding lines were identified from 115 advanced yield trials conducted during *rabi* 2021-22. The experimental materials, like unique registered germplasm, released varieties and exotic lines, were received from the gene bank of the ICAR-Indian Institute of Wheat & Barley Research, Karnal, Haryana, India. The parentage details of the studied research materials are given in Table 1. The Karnal is situated at 29.70°N & 76.99°E and Hisar is located at 29.14°N & 75.70°E. The soil type of Karnal and Hisar is sandy-loam and loamy-sand.

Experimental details

The rainfed experiments were sown during 25–30 October 2022 and no supplementary irrigation was applied during the entire crop period. During the rainfed crop period (up to 20th March 2023), the crop received total rainfall of 14.3 mm and 24.0 mm at Hisar and Karnal locations, respectively. The details of weather parameters recorded are presented in the Supplementary Fig. 1. Under normal irrigated conditions, the irrigated experiments were sown during 05-10 Nov. 2022, following the standard package of practices with full optimum irrigations. The experiments were conducted in the augmented block design (ABD) with 05 blocks, where 04 checks (C306, DBW110, DBW296 and NIAW3170) were repeated in each block randomly in all four environments. The paired rows of 3 m row length spaced 20 cm apart were grown at each location.

Statistical analysis

The data were recorded for days to heading (DH), days to maturity (DM), effective tillers count/m (TPM), spike length

Table 1. Details of the bread wheat germplasm evaluated for water stress tolerance

S No.	Genotype	Sym.	Year	Trait/production condition	ID for registered germplasm	Sr No.	Genotype	Sym.	Year	Trait/production condition	ID for registered germplasm
Trait specific germplasm						37	GW 513	G37	2021	IR-TS-CZ	
1	HINDI 62	G1	1997	Drought tolerance	IC296681	38	HD 3298	G38	2021	VLS-IR-NWPZ	
2	KRL-99	G2	2007	Tolerant to abiotic stress	IC546936	39	MP 1358	G39	2021	RI-TS-PZ	
3	WCF8-HT13	G3	2005	Drought tolerance	IC443622	40	HI 1633	G40	2021	IR-LS-PZ	
4	AKAW3717	G4	2010	Drought tolerance	IC0582907	41	HI 1634	G41	2021	IR-LS-CZ	
5	DWRL1	G5	2012	Lodging resistance	IC0590878	42	HI 1636	G42	2021	IR-TS-CZ	
6	WCF 12-19	G6	2011	Drought tolerance	IC0594378	**Advanced Breeding Lines**					
7	WCF 12-208	G7	2011	Drought tolerance	IC0594379	43	20th HTWYT-43	G43	2021	CIMMYT	
8	WCF 12-61	G8	2011	Drought tolerance	IC0594377	44	20th HTWYT-2	G44	2021	CIMMYT	
9	WCF 12-7	G9	2011	Drought tolerance	IC0594376	45	20th HTWYT-48	G45	2021	CIMMYT	
10	EC 531185	G10	2018	Drought tolerance	EC531185	46	20th HTWYT-25	G46	2021	CIMMYT	
11	HTW63	G11	2019	Drought tolerance	IC36761	47	20th HTWYT-41	G47	2021	CIMMYT	
12	RW5	G12	2020	Drought tolerance	IC635019	48	20th HTWYT-13	G48	2021	CIMMYT	
Released Varieties						49	20th HTWYT-32	G49	2021	CIMMYT	
13	HD2781	G13	2002	RF-TS-PZ		50	20th HTWYT-42	G50	2021	CIMMYT	
14	HD2987	G14	2011	RF/RI-TS-PZ		51	29th SAWYT-334	G51	2021	CIMMYT	
15	HI 1500	G15	2003	RF-TS-CZ		52	29th SAWYT-320	G52	2021	CIMMYT	
16	HI 1531	G16	2006	RF/RI-TS-CZ		53	29th SAWYT-303	G53	2021	CIMMYT	
17	UAS 375	G17	2018	RF-TS-CZ		54	29th SAWYT-341	G54	2021	CIMMYT	
18	HUW 234	G18	1986	IR-LS-NEPZ		55	29th SAWYT-310	G55	2021	CIMMYT	
19	HUW 468	G19	1999	IR-TS-NEPZ		56	29th SAWYT-316	G56	2021	CIMMYT	
20	HW 2004	G20	1997	RF-TS-CZ		57	WAP83	G57	2021	Indigenous sel.	
21	K 8027	G21	1989	RF-TS-NEPZ		58	WAP71	G58	2021	Indigenous sel.	
22	K 9465	G22	1998	RF-LS-NEPZ		59	WAP92	G59	2021	Indigenous sel.	
23	NI 5439	G23	1975	RF/RI-TS-PZ		60	WAP84	G60	2021	Indigenous sel.	
24	NIAW 34	G24	1997	IR-LS-MH		61	WAP75	G61	2021	Indigenous sel.	

Contd.....

25	PBW 175	G25	1989	RF-TS-NWPZ	62	WAP114	G62	2021	Indigenous sel.
26	PBW 596	G26	2009	RF-TS-PZ	63	WAP115	G63	2021	Indigenous sel.
27	PBW 660	G27	2016	RF-TS-NWPZ	64	WAP48	G64	2021	Indigenous sel.
28	WH 1080	G28	2011	RF-TS-NWPZ	65	WAP66	G65	2021	Indigenous sel.
29	WH 1142	G29	2015	RI-TS-NWPZ	66	WAP96	G66	2021	Indigenous sel.
30	HD 3171	G30	2017	RF-TS-NEPZ	67	WAP91	G67	2021	Indigenous sel.
31	K 1317	G31	2018	RF-TS-NEPZ	**Checks**				
32	HI 1612	G32	2018	RI-TS-NEPZ	68	C306	G68	1969	RF-TS-NWPZ
33	HD 3271	G33	2020	VLS-NE/NWPZ	69	DBW110	G69	2015	RI-TS-CZ
34	HI 1621	G34	2020	VLS-IR-NEPZ	70	DBW296	G70	2021	RI-TS-NWPZ
35	HI 1628	G35	2020	RI-TS-NWPZ	71	NIAW3170	G71	2020	RI-TS-NWPZ/PZ
36	HD 3293	G36	2021	RI-TS-NEPZ					

(SL), no. of grains/spike (GPS), and 1000-grain wt. (TKW) and grain yield/plot (GY). In addition, NDVI values and canopy temperature at heading and grain filling stages were also observed with the hand-held devices following standard procedures. The data of all four environments were analysed using the R package Augmented RCBD and pooled analysis of variance was employed as suggested by Federer et al. (2001). The correlation plots were generated using the R package "Metan" in version R 4.1.3. The principal component analysis (PCA) was performed in R 4.1.3 employing FactoMineR, Factoextra and ggplot2 packages. Here, 14 drought stress indices, namely, yield index (YI), tield stability index (YSI), tolerance (TOL), mean productivity (MP), Harmonic mean (HM), drought susceptibility index (DSI), geometric mean productivity (GMP), drought resistance index (DRI), drought tolerance index (DTI), relative drought index (RDI), stress susceptibility per cent index (SSPI), mean relative performance (MRP), percent yield reduction (PYR) and abiotic tolerance index (ATI) were calculated in MS-Excel. These indices were estimated as given in Farshadfar et al. (2014), Singh et al. (2018) and Lamba et al. (2023).

Results

Analysis of variance and mean grain yield

The individual locations analysis of variance (ANOVA) depicted significant mean squares for treatments (eliminating blocks), test entries and check genotypes under stress and favourable environments (Table 2). The combined ANOVA revealed significant mean squares for genotypes, environments and genotype × environment interactions ($p < 0.001$), indicating substantial genetic variations and impact of rainfed conditions on the yield potentials (Supplementary Table S1).

The pooled mean grain yield under water stress was obtained as 610 g, which was reduced by 15.6% to the irrigated conditions. Karnal and Hisar mean rainfed grain yields were observed as 578 g and 642 g, respectively. The test genotype WAP91 ranked first (844 g), followed by HD3171 (831 g), 29th SAWYT-316 (820 g), WAP92 (815 g) and MP1358 (799 g) under stress environment. The check entry NIAW3170 performed better (754 g) than other checks, namely C306 (628 g), DBW296 (587 g) and DBW110 (569 g). The genotypes, namely 20th HTWYT-43 (G43), showed the highest yield reduction under water stress (49.5%), followed by WCF12-61 (G8: 38.03%), AKAW3717 (G4: 37.20%) and HI1612 (G32: 36.9%). Under irrigated conditions, the genotype WAP92 ranked first with 945 g pooled grain yield, followed by 29th SAWYT-310 (935 g), 29th SAWYT-303 (915 g), HI1612 (909 g) and HD3298 (888 g). Location-wise, the genotypes, namely 29th SAWYT-310, WAP92, 29th SAWYT-303, HI1612 and MP1358 were high yielding at Karnal, while at Hisar the genotypes WAP91, WAP114, WAP75, WAP66 and HI1612 performed better.

Table 2. Analysis of variance for individual environments under water stress and irrigated conditions

Source	DF	Mean Sum of Squares (MSS)			
		Rainfed environments		Irrigated environments	
		Karnal	Hisar	Karnal	Hisar
Block (ignoring Treatments)	4	29386.32 **	226989.84 **	75909.27 **	256183.16 **
Treatment (eliminating Blocks)	70	14025.18 **	27382.96 **	11544.36 **	24136.14 **
Block (eliminating Treatments)	4	8027.2	6181.8	1701.2	3330.45
Treatment (ignoring Blocks)	70	15245.7 **	40000.56 **	15784.82 **	38584.87 **
Test and Test *vs.* Check	67	14114.99 **	25480.8 **	10908.88 **	23639.6 **
Treatment: Check	3	12019.4 *	69864.58 **	25736.8 **	35225.65 **
Treatment: Test	66	15452.53 **	39072.37 **	15518.89 **	38385.58 **
Treatment: Test *vs.* Check	1	11274.25 ns	11668.86 *	3480.71 ns	61815.76 **
Residuals	12	3437.07	2427.5	2714.13	4637.98

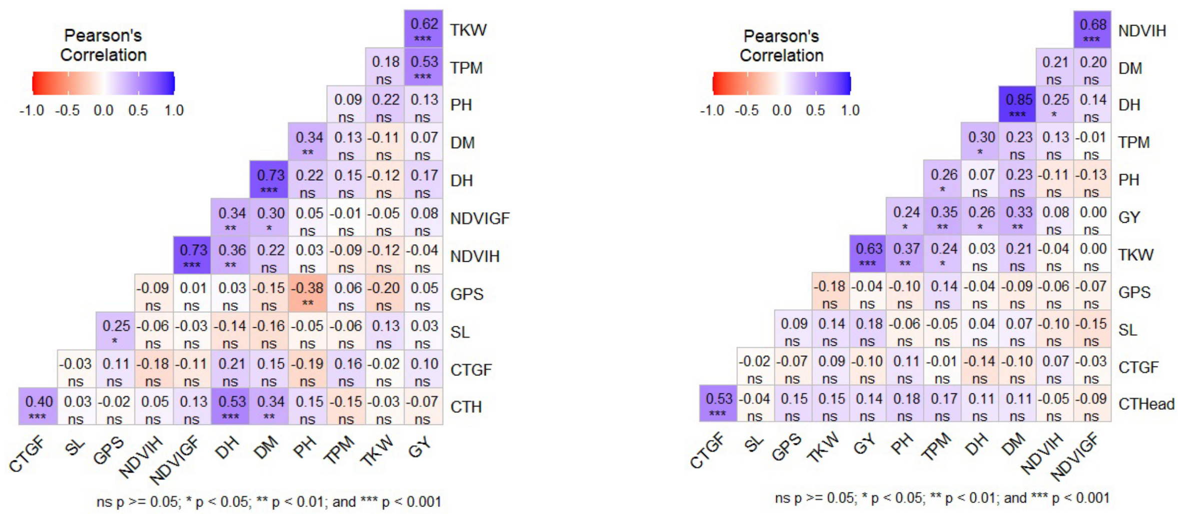

Fig. 1. Correlations under rainfed and irrigated condition

Yield attributes

The genotype 20th HTWYT-32 showed early days to heading (85 days), followed by WCF12-7, EC531185, 29th SAWYT-303, WCF12-19 and WCF12-61 (all ≤ 88 days) under congenial conditions. These genotypes exhibited physiological maturity at 135 days, except 29th SAWYT-303 (138 days). Under water stress condition, 13 genotypes, including 20th HTWYT-13, 25, 32, 41, 43 & 48, GW513, EC531185, WCF12-7, HI1634, HD2987, HUW234 and K9465 showed early spike emergence (≤ 80 days). The genotype DWRL-1 was observed with the shortest plant height under rainfed (58 cm) and irrigated (82 cm) conditions. The other genotypes with short plant height (≤ 95 cm) under irrigated conditions were KRL-99, WCF12-19 and HD2987. Under stress environment, 15 bread wheat genotypes (HD2987, EC531185, NIAW34, 20th HTWYT-25, HI1633, HUW468, KRL-99, etc.)were recorded with plant height ≤ 90 cm. The highest grains/spike were observed for DWRL-1 (80) under moisture stress, followed by 29th SAWYT-320 (73), HI1612 (72), WAP71 (71) and WAP91 (68) under water stress. The genotypes WAP91, WAP83, and HD3298 depicted higher tillers/m under stress conditions. Among check varieties, NIAW3170 had the highest TKW (45 g) and 18 genotypes, including 11 exotic CIMMYT selections, 03 indigenous selections (WAP48, 75 & 96) and 04 released varieties (HI1621, HI1628, DBW296 and K8027) showed higher TKW (>45 g) under rainfed conditions.

Physiological characters

NDVI at heading stage ranged from 0.62 (K8027) to 0.36 (20th HTWYT-2) under water stress, while it varied from 0.78 (HI1531) to 0.38 (HI1628) under irrigated conditions. The genotypes, namely K8027, HI1531, PBW175, UAS375, WH1142, HI1612, K1317, HD3271, WAP96, PBW175, PBW596 and HI1621 showed higher NDVI values both at heading and grain filling stages under water stress conditions. All the check varieties exhibited almost similar NDVI at heading (0.47) and grain filling stages (0.37-0.41) under moisture stress conditions. Under irrigated (IR) condition, the genotypes viz., HI1531 showed the highest NDVI (0.70) at heading stage, followed by UAS375 (0.68), HD3271 (0.68), WAP96 (0.68), K1317 (0.67), 20th HTWYT-25 (0.67), WAP91 (0.67), HI1612 (0.67) and HINDI62 (0.67). Whereas, under irrigated conditions, the genotypes HD3271, UAS375, K9465, HI1531, PBW596 and 29th SAWYT-341, WH1142, HUW234 and HI1612 were found with higher NDVI values (0.54). For canopy temperature at heading stage under stress environment, HUW234, 20th HTWYT-43, NIAW34, WAP91 showed cooler canopy, while the genotypes HUW234, 20th HTWYT-43, HI1628, WCF12-7 and WCF12-19 were promising at the grain filling stage. Under IR conditions, the genotypes EC531185, K1317, WCF12-7, 20th HTWYT-48, K9465, HD3171 and HUW234 showed lower CT at the heading and grain filling stages.

Drought stress indices

Here, 14 widely accepted drought stress indices were estimated and presented in the Supplementary Table S2. The yield index (YI) ranged from 0.39 (DWRL-1) to 1.38 (WAP91) and the stress-tolerant genotypes identified with higher YI are WAP91 (1.38), HD3171 (1.36), 29th SAWYT-316 (1.34), WAP92 (1.34) and MP1358 (1.31). YSI, MP, HM and GMP ranged from 0.50 (20th HTWYT-43) to 1.06 (K9465), 276.7 (DWRL-1) to 879.7 (WAP92), 271 (DWRL-1) to 874.9 (WAP92) and 273.8 (DWRL-1) to 877.3 (WAP92), respectively. Among the checks, the lowest DSI was depicted by NIAW3170 (0.78), whereas the genotype K9465 ranked first, followed by HD2987, K8027, 29th SAWYT-316, WAP91, HD3171, 20th HTWYT-48 and PBW596 (all<0.30). Based on SSPI, PYR and ATI, the genotype K9465 ranked first, followed by HD2987 and K8027.

Morpho-physiological correlations

Under moisture stress conditions, days to heading (DH) showed positive and significant correlations (r=0.73**) with days to maturity (DM), while plant height (PH) showed negative correlations with grains/spike (r=-0.38**) (Figure 1). Grain yield (GY) showed positive and significant associations with 1000-grain wt. (TKW: r=0.62***) and tillers/m (r=0.53***).While under irrigated conditions, GY showed positive and significant associations with DH (r=0.26*), DM (r=0.33**), tiller count (0.35**), PH (0.24*) and TKW (0.63**). Under water stress, NDVI at heading (NDVIH) was found to be positively associated with days to heading, NDVI at grain filling, whereas the canopy temperature at heading (CTH) exhibited a positive relationship with DH, DM and CT at grain filling (CTGF). NDVIH and CTH showed a positive association with NDVIGF and CTGF, respectively, under favourable conditions.

Drought stress indices correlations

Yield index showed positive and significant correlations with YSI (r=0.62***), RDI (r=0.62***), DRI (0.96***), STI (r=0.97***), HM (r=0.98***), MP (r=0.96***), GMP and MRP (both r=0.97***) (Figure 2). Drought susceptibility index (DSI) exhibited a positive and significant association with PYR,

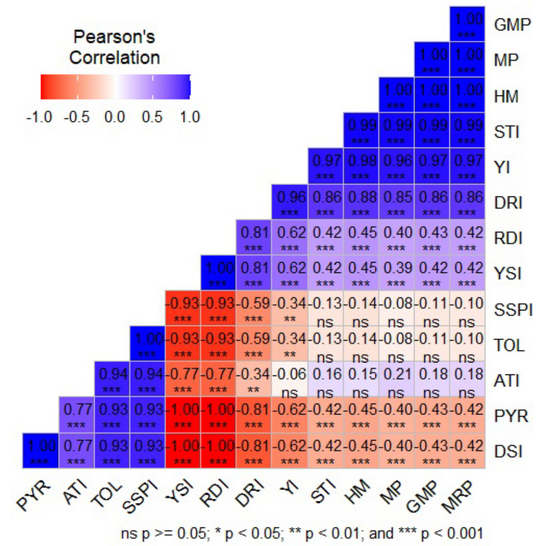

Fig. 2. Correlations among 14 drought stress indices

ATI, TOL and SSPI, while it depicted negative correlations with YI, YSI, RDI, DRI, STI, HM, MP, GMP and RMP. Here, the complete associations (r=1.00***) were observed between DSI and PYR, TOL and SSPI, YSI and RDI and among HM, MP, GMP and MRP.

Principal Component analysis (PCA)

Indices-based PCA was carried out to understand the distribution of the genotypes (Fig. 3). The initial two principal components (PCs) captured 65.9% and 33.2% of the total variation. The standard deviation (SD) based PCA biplot revealed that the estimated 14 drought stress indices were grouped into three clusters. The indices, namely PYR, DSI, SSPI, TOL and ATI, were grouped into a single segment. An individual cluster was obtained for HM, GMP, MRP, MP, STI, YI and DRI. The indices RDI and YSI were clustered into a different quadrant. The genotypes G30 (HD3171), G39 (MP1358), G45 (20th HTWYT-48), G56 (29th SAWYT-316) and G67 (WAP91) were found high yielding and water stress tolerant.

Discussion

The pooled crop yield showed a reduction of 15.6% under water stress, while days to heading, tiller count and plant height were reduced by 8.1, 15.5, and 12.5%, respectively. The wheat genotypes, WAP84, PBW596, 20thHTWYT-48, HD3171, WAP91, 29th SAWYT-316, K8027, K9465 and HD2987 were identified with the lowest grain yield reduction (<5.0%). It was observed that the drought susceptible genotypes depicted a significant decrease in tiller count, plant height and 1000 grain wt. Whereas, the tolerant genotypes were found with the moderate reduction for plant height and tiller count, but largely maintained 1000 grain wt. under water stress. Sarwar et al. (2023) reported that the tillering stage is extensively susceptible to drought stress and reduces

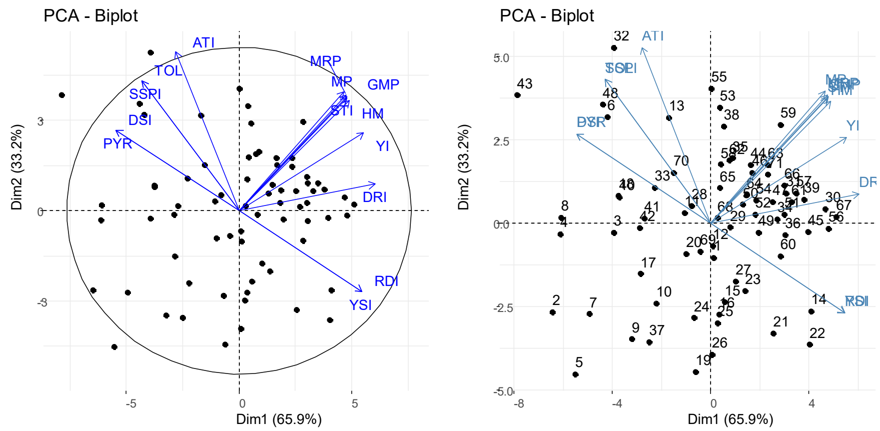

Fig. 3. PCA biplot for drought stress indices and grouping of genotypes

tiller count significantly. The commonly used parents in the drought stress breeding programs, namely HI1500, NI5439, NIAW34 and PBW175, also showed minimum grain yield reduction (<10%). Whereas, the most popular two genotypes, HINDI62 and C306, exhibited 12.8% and 15.3% yield loss under water stress. However, all of these genotypes were lower yielders (≥25%) than the best check, NIAW3170.

Garg et al. (2012) summarized that high proline, lower H_2O_2 and increased antioxidant enzymatic activity are some of the key characteristics for drought tolerance in C306 and HD2382. Morphologically, root system architecture, leaf senescence, stay green habit and rapid flowering (early maturity) triggered by earliness *per se* (*Eps*) and photoperiod (*Ppd*) gene(s) are some effective mechanisms to tackle water stress (Farooq et al. 2014). Here, the early flowering by 5-10 days was observed under water stress; however, most of the tolerant genotypes compensated for grain yield by a prolonged grain filling period. Singh et al. (2012) reported that C306 can alleviate drought effects by curtailing lipid peroxidation. The well-reported biochemical mechanisms of drought tolerance are functional protection of proteins, accumulation of osmolytes, induction of antioxidant defence and hormonal regulations (Fleury et al. 2010; Budak et al. 2013; Nezhadahmadi et al. 2013; Mwadzingeni et al. 2016; Adel and Carels 2023).

In the present study, 14 drought stress indices were calculated to identify drought-tolerant genotypes. Drought susceptibility index (DSI) is most widely used in the stress breeding programs (Fischer and Maurer 1978; Mall et al. 2011; Mohammed et al. 2021; Negisho et al. 2022); however, it does not provide substantial information for yield advantage coupled with stress resilience. For instance, here the genotypes K9465, HD2987 and K8027 were the three top rankers for DSI but showed yield reduction of

Table 3. Per cent reduction under water stress and ranking based on drought resistance index (DRI)

Geno Sym.	Genotype	DSI rank	DRI rank	Yield advantage over the best check	Percent reduction under water stress						
					GY	DH	PH	TPM	SL	GPS	TKW
G67	WAP91	5	1	11.9	2.2	7.8	13.4	6.9	8.3	6.7	3.9
G56	29th SAWYT-316	4	2	8.7	2.0	9.3	19.4	11.7	1.9	10.2	0.4
G30	HD 3171	6	3	10.2	3.7	7.2	10.0	15.4	4.3	4.3	2.3
G45	20th HTWYT-48	7	4	3.3	3.9	11.9	14.0	12.6	14.3	0.3	2.1
G39	MP 1358	13	5	5.9	6.6	7.0	13.9	17.0	14.9	1.2	2.4
G57	WAP83	18	7	4.9	7.8	8.5	13.0	10.1	11.1	4.2	1.3
G61	WAP75	17	9	2.7	7.8	12.2	12.2	8.3	8.2	14.4	0.8
G59	WAP92	35	10	8.0	13.8	5.9	12.9	14.8	6.3	11.9	3.3
G31	K 1317	22	11	2.3	9.0	6.2	12.7	19.7	0.0	3.5	0.4
G66	WAP96	24	12	2.9	9.6	8.3	17.3	7.4	8.0	1.9	1.4
G63	WAP115	30	18	1.0	12.7	8.6	19.0	9.8	11.8	28.9	8.1
G71	NIAW3170 (c)	29	19	-	12.0	7.2	4.2	18.6	11.1	8.1	0.4

10.4, 5.5, and 17.4% over the best check NIAW3170 under rainfed conditions. These genotypes also appeared as stress-tolerant in the estimated indices, namely YSI, TOL, RDI, SSPI, PYR and ATI (Supplementary Table 3). In general, the genotypes having minimum yield variations under water stress and irrigated conditions were identified by the above stress indices and presented as drought-tolerant. However, the yield potential of the genotypes cannot be ignored, particularly in the stress breeding programs. The high-yielding potential and drought-tolerant parents are likely to throw more desirable segregants in the filial generations with the favourable gene constellations. Mohammadi et al. (2016) reported that SSI, YSI and TOL showed variable concordance values and were inaccurate under drought conditions. Based on yield and stress resilience, the drought resistance index (DRI) was more successful in identifying tolerant genotypes under moisture stress.

The genotypes *viz.*, WAP91 (G67), 29th SAWYT-316 (G56), HD3171 (G30), 20th HTWYT-48 (G45) and MP1358 (G39) were the top five rankers based on DRI (Table 3). All these genotypes revealed a grain yield advantage (3.3–11.9%) over the best check NIAW3170, coupled with minimum grain yield reduction under water stress (2.2–6.6%). While comparing DRI and DSI, we found that WAP92 (G59) ranked 10th for DRI and 35th in DSI, depicting a yield advantage of 8.0% over the best check; however, it showed a 13.8% yield reduction. The other promising genotypes identified based on DRI were, namely, WAP75, WAP83, WAP96 and K1317. The other stress indices, YI, MP, HM, GMP and MRP, also substantiated better yielding stress-tolerant genotypes, but were not found as effective as DRI. The PCA biplots generated for genotypes and stress indices also classified DRI with an acute angle, long vector length and better representativeness.

The exotic lines, 29th SAWYT-316 (G56) and 20th HTWYT-48 (G45), were studied for genealogy and the water resilience in G45 could be attributed to one of the parents, CROC_1/*Ae. squarrosa*. The genotype G56 probably possessed water stress tolerance gene(s) and genomic regions from the climate resilient genotypes, Kachu and Kiritati. Similarly, the released wheat variety HD3171 possibly gained water resilience from HD2879, while MP1358 from Kachu and K1215. The genealogy found is in agreement with the findings of Meena et al. (2025), who reported the common parent Kiritati in the parentage of the water-use-efficient bread wheat genotypes, 40th ESWYT-07 and 40th ESWYT-37. Among the employed drought tolerance indices, the drought resistance index (DRI) was the most successful in identifying stress-tolerant and high-yielding genotypes. The genotypes, namely HD3171, MP1358, 20th HTWYT-48, 29th SAWYT-316, K1317 and WAP91 appeared as drought tolerant. The yield attributes 1000 grain weight, grains/spike and tillers count can be targeted as selection under drought stress breeding programs and to train genomic models.

Supplementary materials

The Supplementary Tables S1 to S3 and Supplementary Fig. 1 are provided, which can be accessed at www.isgpb.org

Authors' contribution

Conceptualization of research (VK, VS, AG); Designing of the experiments (VK, VS, VG, SK); Contribution of experimental materials (VK, AG); Execution of field experiments and data collection (VK, VS, VG); Analysis of data and interpretation (VK, GPS); Preparation of the manuscript (VK, GPS).

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Supplementary Table S1. Combined analysis of variance for stress and irrigated conditions

Source	df	SS	MSS	F Value	Pr
Environment (Env.)	1	905018	905018	273.90	P<.001
Genotype (Geno)	70	5384351	76919	12.35	P<.001
Rep (Env.)	2	324333	162167	49.07	P<.001
Geno × Env.	70	435857	6227	1.88	P<.001
Pooled Error	140	462583	3304.17	-	-

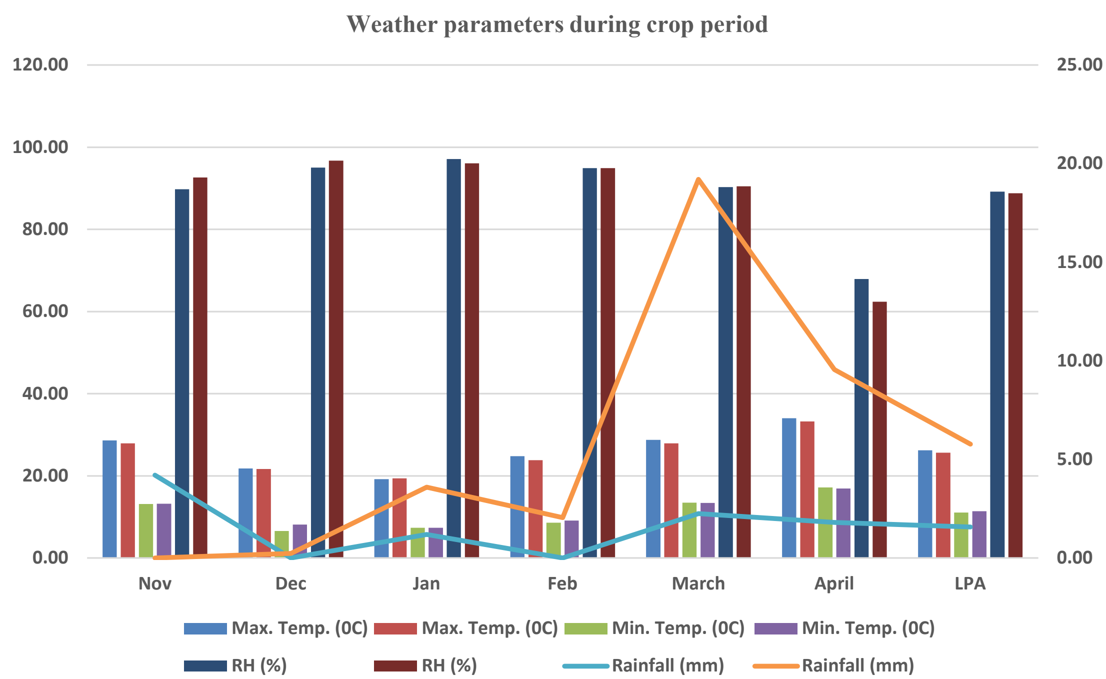
Supplementary Table 2. Estimated drought stress indices for bread wheat genotypes

Genotype	Sym.	YI	YSI	TOL	MP	HM	DSI	GMP	DRI	STI	RDI	SSPI	MRP	PYR	ATI
HINDI 62	G1	0.96	0.87	86.35	630.20	627.24	0.82	628.72	511.75	0.76	1.03	5.97	1.89	12.82	480.44
KRL-99	G2	0.43	0.66	137.35	332.70	318.52	2.19	325.53	173.68	0.20	0.78	9.50	0.99	34.22	395.68
WCF8-HT13	G3	0.71	0.71	174.35	523.20	508.67	1.83	515.89	311.48	0.51	0.85	12.06	1.56	28.56	795.97
AKAW3717	G4	0.57	0.63	204.35	447.20	423.86	2.38	435.37	216.69	0.36	0.74	14.13	1.33	37.20	787.33
DWRL1	G5	0.39	0.75	79.35	276.70	271.01	1.61	273.84	177.58	0.14	0.89	5.49	0.83	25.08	192.29
WCF 12-19	G6	0.84	0.65	280.35	653.20	623.12	2.27	637.98	331.74	0.78	0.77	19.39	1.94	35.34	1582.82
WCF 12-208	G7	0.53	0.73	120.35	382.20	372.73	1.74	377.43	234.42	0.27	0.86	8.32	1.14	27.21	401.98
WCF 12-61	G8	0.59	0.62	220.35	469.20	443.33	2.44	456.08	222.48	0.40	0.74	15.24	1.39	38.03	889.36
WCF 12-7	G9	0.60	0.82	81.35	407.70	403.64	1.16	405.67	300.43	0.31	0.97	5.63	1.22	18.14	292.04
EC 531185	G10	0.73	0.83	92.85	490.45	486.06	1.11	488.25	367.23	0.46	0.98	6.42	1.47	17.29	401.18
HTW63	G11	0.94	0.80	140.85	644.45	636.75	1.26	640.59	460.93	0.79	0.95	9.74	1.93	19.70	798.47
RW5	G12	0.98	0.86	95.35	643.70	640.17	0.88	641.93	513.83	0.79	1.02	6.59	1.93	13.79	541.67
HD2781	G13	1.02	0.73	229.85	735.95	718.00	1.73	726.92	453.27	1.01	0.87	15.90	2.19	27.01	1478.61
HD2987	G14	1.17	1.03	-21.65	701.70	701.53	-0.20	701.62	734.85	0.94	1.22	-1.50	2.12	-3.13	-134.42
HI 1500	G15	0.93	0.92	48.35	588.70	587.71	0.51	588.20	519.99	0.66	1.09	3.34	1.77	7.89	251.68
HI 1531	G16	0.89	0.92	44.35	565.70	564.83	0.48	565.27	502.52	0.61	1.10	3.07	1.70	7.54	221.85
UAS 375	G17	0.73	0.78	124.35	506.70	499.07	1.40	502.87	347.36	0.48	0.93	8.60	1.52	21.86	553.38
HUW 234	G18	0.78	0.70	202.35	575.70	557.92	1.92	566.74	332.67	0.61	0.83	13.99	1.71	29.89	1014.87
HUW 468	G19	0.72	0.95	25.35	454.20	453.85	0.35	454.02	417.55	0.39	1.12	1.75	1.37	5.43	101.85
HW 2004	G20	0.89	0.83	109.35	596.20	591.19	1.08	593.69	450.55	0.67	0.99	7.56	1.79	16.80	574.51
K 8027	G21	1.02	1.01	-5.65	619.70	619.69	-0.06	619.69	628.23	0.73	1.20	-0.39	1.87	-0.92	-30.98
K 9465	G22	1.11	1.06	-39.15	655.45	654.87	-0.39	655.16	716.59	0.82	1.26	-2.71	1.99	-6.16	-226.99
NI 5439	G23	1.00	0.94	41.85	632.45	631.76	0.41	632.10	572.36	0.76	1.11	2.89	1.91	6.41	234.10
NIAW 34	G24	0.81	0.89	58.35	524.70	523.08	0.68	523.89	443.32	0.53	1.06	4.04	1.58	10.53	270.52
PBW 175	G25	0.87	0.93	40.35	551.70	550.96	0.45	551.33	494.02	0.58	1.10	2.79	1.66	7.06	196.87
PBW 596	G26	0.80	0.95	23.85	502.45	502.17	0.30	502.31	467.78	0.48	1.13	1.65	1.52	4.64	106.02
PBW 660	G27	0.99	0.92	54.35	631.20	630.03	0.53	630.61	554.16	0.76	1.09	3.76	1.90	8.26	303.31
WH 1080	G28	0.97	0.81	142.35	662.20	654.55	1.24	658.36	476.31	0.83	0.96	9.84	1.98	19.41	829.36
WH 1142	G29	1.05	0.87	95.35	690.70	687.41	0.83	689.05	559.99	0.91	1.03	6.59	2.08	12.91	581.43
HD 3171	G30	1.36	0.96	32.35	847.20	846.89	0.24	847.05	799.89	1.37	1.14	2.24	2.56	3.75	242.49
K 1317	G31	1.26	0.91	76.35	809.20	807.40	0.58	808.30	701.55	1.25	1.08	5.28	2.44	9.01	546.14
HI 1612	G32	0.94	0.63	336.35	741.20	703.04	2.37	721.87	361.08	1.00	0.75	23.26	2.20	36.99	2148.68
HD 3271	G33	0.89	0.75	184.35	634.20	620.80	1.63	627.47	404.46	0.75	0.89	12.75	1.89	25.38	1023.66
HI 1621	G34	1.20	0.92	65.35	766.70	765.31	0.52	766.00	674.02	1.12	1.09	4.52	2.31	8.18	442.99
HI 1628	G35	1.15	0.83	145.35	775.70	768.89	1.10	772.29	582.58	1.14	0.98	10.05	2.33	17.13	993.38
HD 3293	G36	1.21	0.94	47.35	759.70	758.96	0.39	759.33	691.54	1.10	1.11	3.27	2.29	6.04	318.18

GW 513	G37	0.64	0.85	70.35	428.20	425.31	0.97	426.75	333.36	0.35	1.01	4.87	1.29	15.18	265.68
HD 3298	G38	1.17	0.80	177.35	799.70	789.87	1.28	794.77	569.08	1.21	0.95	12.26	2.39	19.96	1247.36
MP 1358	G39	1.31	0.93	56.85	826.95	825.97	0.43	826.46	745.45	1.31	1.11	3.93	2.49	6.65	415.79
HI 1633	G40	0.78	0.70	200.85	573.20	555.61	1.91	564.33	331.81	0.61	0.83	13.89	1.71	29.82	1003.07
HI 1634	G41	0.82	0.75	165.85	581.70	569.88	1.60	575.76	374.31	0.63	0.89	11.47	1.74	24.95	845.04
HI 1636	G42	0.79	0.75	160.85	564.20	552.74	1.60	558.44	363.06	0.60	0.89	11.12	1.68	24.95	794.91
20^{th} HTWYT-43	G43	0.62	0.50	369.85	561.70	500.82	3.18	530.39	190.13	0.54	0.60	25.58	1.65	49.54	1735.96
20^{th} HTWYT-2	G44	1.20	0.85	124.85	794.20	789.29	0.93	791.74	625.12	1.20	1.01	8.63	2.38	14.57	874.77
20^{th} HTWYT-48	G45	1.28	0.96	31.85	794.70	794.38	0.25	794.54	748.18	1.21	1.14	2.20	2.40	3.93	223.95
20^{th} HTWYT-25	G46	1.19	0.86	118.85	786.20	781.71	0.90	783.95	624.63	1.18	1.02	8.22	2.36	14.05	824.54
20^{th} HTWYT-41	G47	1.21	0.90	80.85	781.20	779.11	0.63	780.15	667.88	1.16	1.07	5.59	2.35	9.84	558.19
20^{th} HTWYT-13	G48	0.84	0.64	294.85	662.20	629.38	2.33	645.58	327.30	0.80	0.75	20.39	1.96	36.42	1684.51
20^{th} HTWYT-32	G49	1.13	0.91	70.85	724.20	722.47	0.60	723.33	624.53	1.00	1.08	4.90	2.18	9.33	453.52
20^{th} HTWYT-42	G50	1.12	0.87	102.85	735.20	731.60	0.84	733.40	594.37	1.03	1.03	7.11	2.21	13.07	667.52
29^{th} SAWYT-334	G51	1.23	0.92	61.85	782.70	781.48	0.49	782.09	694.63	1.17	1.10	4.28	2.36	7.60	428.07
29^{th} SAWYT-320	G52	1.14	0.89	85.85	740.70	738.21	0.70	739.46	621.33	1.05	1.06	5.94	2.23	10.96	561.79
29^{th} SAWYT-303	G53	1.18	0.79	195.10	817.20	805.56	1.37	811.36	566.16	1.26	0.93	13.49	2.44	21.33	1400.85
29^{th} SAWYT-341	G54	1.17	0.88	95.10	759.20	756.22	0.76	757.71	627.76	1.10	1.05	6.58	2.28	11.79	637.68
29^{th} SAWYT-310	G55	1.17	0.77	218.10	825.70	811.30	1.50	818.47	549.44	1.28	0.91	15.08	2.47	23.33	1579.71
29^{th} SAWYT-316	G56	1.34	0.98	17.10	828.20	828.11	0.13	828.16	802.90	1.31	1.16	1.18	2.50	2.04	125.32
WAP83	G57	1.30	0.92	67.10	824.20	822.83	0.50	823.52	728.80	1.30	1.09	4.64	2.48	7.82	489.01
WAP71	G58	1.11	0.82	150.10	752.70	745.22	1.16	748.95	554.77	1.07	0.97	10.38	2.26	18.13	994.84
WAP92	G59	1.34	0.86	130.10	879.70	874.89	0.88	877.29	702.47	1.47	1.02	9.00	2.64	13.77	1010.05
WAP84	G60	1.16	0.95	37.10	726.20	725.73	0.32	725.96	672.40	1.01	1.13	2.57	2.19	4.98	238.35
WAP75	G61	1.27	0.92	65.10	807.20	805.89	0.50	806.54	714.60	1.24	1.09	4.50	2.43	7.75	464.65
WAP114	G62	1.14	0.83	147.10	768.20	761.16	1.12	764.67	573.26	1.12	0.98	10.17	2.30	17.48	995.43
WAP115	G63	1.25	0.87	111.10	817.20	813.42	0.82	815.31	664.69	1.27	1.04	7.68	2.46	12.73	801.60
WAP48	G64	1.15	0.87	107.10	753.20	749.39	0.85	751.29	606.77	1.08	1.03	7.41	2.26	13.28	712.07
WAP66	G65	1.08	0.83	133.10	723.20	717.08	1.08	720.13	545.98	0.99	0.99	9.20	2.17	16.85	848.23
WAP96	G66	1.27	0.90	82.10	816.70	814.64	0.61	815.67	701.41	1.27	1.07	5.68	2.46	9.57	592.62
WAP91	G67	1.38	0.98	19.10	853.20	853.09	0.14	853.15	824.97	1.39	1.16	1.32	2.58	2.21	144.20
Checks															
C306	G68	1.03	0.85	113.10	684.05	679.38	0.98	681.71	531.67	0.89	1.01	7.82	2.05	15.27	682.31
DBW110	G69	0.93	0.85	101.00	619.30	615.18	0.97	617.24	483.03	0.73	1.01	6.98	1.86	15.08	551.69
DBW296	G70	0.96	0.76	181.40	677.90	665.76	1.51	671.80	448.61	0.86	0.91	12.54	2.03	23.60	1078.46
NIAW3170	G71	1.24	0.88	103.90	805.55	802.20	0.78	803.87	662.29	1.24	1.04	7.19	2.42	12.12	739.14

Supplementary Table 3: Drought tolerant genotypes identified based on different stress indices

YI	HD3171, MP1358, 29th SAWYT-316, WAP92, WAP91
YSI	K9465, HD2987, K8027, 29th SAWYT-316, WAP91
TOL	K9465, HD2987, K8027, 29th SAWYT-316, WAP91
MP	WAP92, WAP91, 29th SAWYT-316, MP1358, HD3171
HM	WAP92, WAP91, 29th SAWYT-316, MP1358, HD3171
DSI	WAP91, 29th SAWYT-316, K9465, K8027, HD2987
GMP	WAP92, WAP91, 29th SAWYT-316, MP1358, HD3171
DRI	WAP91, 29th SAWYT-316, HD3171, 20th HTWYT-48, MP1358
STI	WAP92, WAP96, 29th SAWYT-316, HD3171, MP1358
RDI	K9465, HD2987, K8027, 29th SAWYT-316, WAP91
SSPI	K9465, HD2987, K8027, 29th SAWYT-316, WAP91
MRP	WAP92, WAP91, 29th SAWYT-316, MP1358, HD3171
PYR	K9465, HD2987, K8027, 29th SAWYT-316, WAP91
ATI	K9465, HD2987, K8027, HUW468, PBW596
PCAbiplot based	WAP91, 29th SAWYT-316, HD3171, 20th HTWYT-48, MP1358



Supplementary Fig. 1. Weather parameters recorded during crop period