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Research Article

Comparative analysis of trait associations in wheat: Insights from irrigated and drought stress cropping systems

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ABSTRACT- Breeders need to understand how traits relationship help create effective breeding programs. An investigation involving eight wheat cultivars was carried out to assess trait relationships in the climate of Dashtestan County, Bushehr province (Iran). The experiment included both irrigated and drought stress conditions during the 2023-2024 cropping season. Statistical techniques, including the Pearson correlation and factor analysis, were employed to analyze the data collected from the two contrasting growing conditions. The correlation patterns among wheat traits varied significantly between irrigated and drought stress systems. However, traits related to the yield, such as tiller number per plant, spikelet number, and grain number per spike, showed a positive correlation with the grain yield in both conditions. Under irrigated cultivation conditions, factor analysis identified four key factors influencing crop yields. These factors, presented in descending order of significance, were agronomic and yield potential, yield components, phenology, and the tiller number per plant. Based on these findings, the Chamran cultivar showed high potential for cultivation under irrigated conditions. Under drought stress conditions, factor analysis identified four main patterns that accounted for 86.3% of the variation observed in the traits. The analysis revealed four essential factors that significantly influenced the crop yield. These factors, presented in descending order of importance, were plant yield, plant structure, reproductive traits, and flag leaf length and phenology.

INTRODUCTION

Bread wheat (*Triticum aestivum* L.) is the world's most important crop and plays a vital role in food security. This crop, cultivated in most parts of the world due to its adaptability to diverse conditional conditions, provides about 21% of human calories and 20% of protein (Shokat *et al*., 2023). Understanding the relationships between different agronomic traits in this plant is essential for enhancing its yield and quality. Studying wheat cultivar grain yield and trait interactions under both drought stress and irrigated conditions provides valuable information about their genetic background, key factors affecting yield, drought resistance, and how the plants function. However, these relationships can be influenced by conditional factors such as cultivation conditions. For instance, in a study on irrigated wheat cultivation conditions, thousand-kernel weight had the greatest impact on grain yield, while in drought stress cultivation conditions, spike length was found to have the most significant effect (Afrooz *et al*, 2014). Plants grown under drought stress conditions are exposed to conditional stresses, such as water scarcity, which can significantly impact trait relationships. These stresses can lead to changes in trait priorities and relationships. Drought stress has been shown to reduce the number of days to heading and maturity, grain yield per spike, yield, and chlorophyll content, and to increase proline in drought stress wheat cultivation (Chowdhury *et al*., 2021). Research on wheat grown in drought stress and irrigated conditions showed that conditional signals prompt the plant to utilize various tactics to maximize grain production (Arriagada *et al*., 2022). Under irrigated conditions, the emphasis was on increasing the number of grains per unit area, while under drought stress conditions, the emphasis was on increasing grain weight to maximize water storage (Khadka *et al*., 2020). Naghavi and Khalili (2017) utilized factor analysis to examine the inter-trait relationships among 15 wheat cultivars under irrigated and drought stress cultivation conditions. Under drought stress conditions, plant growth-related traits emerged as a distinct factor influencing yield, whereas this observation was not evident under irrigated cultivation. Furthermore, under dry conditions (unlike irrigated cultivation), cultivars displaying growth-related traits were classified into a distinct group in this experiment. A two-year study involving 119 wheat genotypes grown under varying cultivation conditions in Ethiopia revealed distinct patterns of inter-trait relationships among morpho-

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physiological traits (Sewore & Nigussie, 2023). Principal component analysis (PCA) revealed that different traits played crucial roles in each cultivation condition based on their importance and contribution to the overall variation among genotypes. Wheat production in the southern provinces of Iran, including Bushehr, faces challenges due to conditional stresses such as drought. Located in southern Iran, this province is among the low-precipitation provinces of the country. The province receives an average annual rainfall of 246 millimeters, placing it among the regions with high water stress. The area under wheat cultivation in Bushehr Province in 2022 was reported to be 220.6 hectares (Ministry of Agricultural Jihad, 2022). The objective of this study was to compare the relationships between traits and the grouping of eight wheat cultivars under drought stress and irrigated conditions in the Dashtestan County, Bushehr province, Iran.

MATERIALS AND METHODS

Eight wheat cultivars, namely Chamran, Koohdasht, Dehdasht, Karim, Ghabous, Savarz, Mehrgan, and Aftab were acquired from the Agricultural Jihad Organization of Bushehr Province and the Gachsaran Dryland Agricultural Research Station in southern Iran. The experiment was conducted at the research farm of the Faculty of Agricultural Engineering at Persian Gulf University during the 2022-2023 cropping season. The farm is located 8 km southeast of the center of Dashtestan County, Bushehr province (Iran). The soil texture of the farm was 10.5% sand, 47% silt, and 42% clay. Land preparation operations, including plowing, disking, and leveling were carried out in early October. Chemical fertilizers were applied to the land at a rate of 200 kg/ha of ammonium phosphate, 150 kg/ha of urea, and 150 kg/ha of potassium sulfate. Part of the nitrogen fertilizer was applied as a top dressing during the tillering and stem elongation stages. The agricultural climate of the region is characterized by very hot and dry summers. Table 1 shows the meteorological statistics of Borazjan (the central city of Deshtestan County) during the experimental period. Based on this, the amount of rainfall during the cultivation period of the varieties was 10.55 mm, and the amount of evaporation from the pan was 48.55 mm (4.6 times the amount of rainfall). Additionally, the average air temperature and relative humidity during the plant growth period were 23.6 °C and 53.5%, respectively (Table 1).

Due to the uncertainty of rainfall occurrence, to ensure consistent results for comparing cultivars and evaluating their yield potential, this experiment was conducted under drought stress conditions as well as with supplementary irrigation. The results obtained from both methods were compared at the end. Irrigation in irrigated cultivation was carried out using a drip system tailored to the water requirements of the crops in the region. The Penman-Monteith technique was employed to calculate the amount of water (Allen *et al*., 1998). The crops were planted simultaneously on December 11, 2023. The experiment was conducted in a field, side by side, each using a randomized complete block design with three replications. In this study, a 50% water deficit was imposed on plants to simulate dryland cropping conditions. This level of water stress was considered representative of the variable water stress conditions commonly found in dryland areas. This level of stress allowed for an investigation into the effects of water stress on the studied traits without compromising the plant's ability to reach full maturity. Moreover, comparing plants under drought stress with well-watered plants enabled us to identify the differences attributed solely to water stress. To induce drought stress, three soil samples were collected from the root zone depth (up to 20 cm) at various locations in the field every 24 hours during the plant growth period following irrigation. The samples were weighed and then placed in an oven at 100 °C to measure weight and moisture content. Subsequently, the soil moisture content at field capacity was determined, and the initial moisture content in the soil before applying treatments with varying stress levels was assessed. The analysis of variance (ANOVA) table for this investigation included the two cultivation methods, which were deemed functionally equivalent within their respective conditions. In addition to grain yield per unit area, 14 other traits were measured, including grain yield per spike (g), grain yield per plant (g), tiller number per plant, fertile tiller number per plant, spikelet number, grain number per spike, plant height (cm), leaf number per plant, number of days to flowering, thousand-kernel weight (g), awn length (cm), spike length (cm), flag leaf length (cm), and peduncle length (cm). The traits under study were measured on ten randomly selected plants from each experimental unit, following the measurement methods described in the Wheat Descriptor List (IBPGR, 1985). Planting row spacing was set at 25 cm, planting depth at 5 cm, and a density of 300 seeds per square meter. 2,4-D herbicide was applied to control weeds during the late tillering stage. Confidor systemic insecticide was applied during the late stem elongation stage to control insects. Each experimental unit consisted of 14 planting rows that were 4 meters long. The cultivars were harvested in mid-May of the following year. After testing the normality of the data using the Kolmogorov-Smirnov test, the combined analysis of variance was conducted using SAS software (version 9.4). When a significant interaction between condition and genotype was detected, a slice analysis (using SAS software) was conducted to compare genotypes within each condition.

RESULTS AND DISCUSSION

Table 2 shows the results of the combined analysis of data. The interaction between cultivar and condition was significant for all traits except the number of days to flowering, awn length, and spike length.

To investigate the interaction, slicing analysis was performed for each condition for this group of traits, followed by a comparison of cultivar means in both conditions (Table 3). The yield of different wheat cultivars for various traits was significantly affected by drought stress in a drought stress system. According to Table 3, the mean values of traits, including the tiller number per plant, fertile tiller number per plant, plant height, thousand-kernel weight, peduncle length, grain yield per plant, grain yield per spike, and total grain yield were lower under drought stress conditions with stress compared to irrigated conditions (LSD; $P < 0.05$). In general, the occurrence of drought stress affects the rate of photosynthesis by altering the internal structure of chloroplasts, mitochondria, and chlorophyll content (Ahmad et al., 2018). Drought stress leads to an increase in reactive oxygen species (ROS) in plants. These molecules damage chloroplasts. Stomatal closure also reduces the entry of carbon dioxide into plants. Consequently, seed yield is reduced (Farooq et al., 2014). Given its yield in two conditions, drought stress resistance and good performance under drought stress conditions, the Koohdasht cultivar could be a suitable choice for cultivation in water-scarce regions like Dastestan.

Correlation analysis

Under irrigation condition, grain yield had a significant positive correlation with the tiller number per plant (0.570), fertile tiller number per plant (0.768), spikelet number (0.816), grain yield per spike (0.872), spike length (0.755), grain yield per plant (0.978), and grain yield per spike (0.538). It had a significant negative correlation with thousand-kernel weight (-0.776) and awn length (-0.812) (Table 4).

Under drought stress condition, grain yield had a significant positive correlation with the tiller number per plant (0.845), fertile tiller number per plant (0.874), grain number per spike (0.848), plant height (0.820), spike length (0.671), peduncle length (0.760), grain yield per plant (0.992), and grain yield per spike (0.813). It had a significant negative correlation with thousand-kernel weight (-0.560) (Table 5). Similar findings were reported under drought stress conditions in the study by Zarei et al. (2013).

Table 1. Meteorological data for Dashtestan County, Bushehr province (Iran) during the 2022-2023 growing season

Month	Mean precipitation (mm)	Mean evaporation from tank (mm)	Mean relative humidity (%)	Mean temperature (°C)	Mean minimum temperature (°C)	Mean maximum temperature (°C)
October	0	8.26	50	32	24.3	39.8
November	1.3	4.8	65	26.1	20.5	31.7
December	3.4	2.89	70	20.9	15.3	26.4
January	5.1	2.29	82	15.2	11.4	19
February	1.15	2.53	75	15.9	11.1	20.6
March	0.2	5.56	57	22.9	16.1	29.6
April	0.7	7.57	45	23.8	16.2	31.3
May	0	11.28	23	30.9	22.3	39.5
June	0	16.43	23	35.9	44.4	27.4

Table 2. Combined analysis of measured traits in 8 wheat cultivars under irrigated and drought stress conditions

	Source of variation	Condition	Error 1	Cultivar	Cultivar × Condition	Error 2	Coefficient of variation (%)
Mean square	Degree of freedom	1	4	7	7	28	
	Tiller number per plant	9.90**	0.13	4.51**	0.68*	0.24	5.78
	Fertile tiller number per plant	24.51**	0.08	10.47**	1.33**	0.12	6
	Spikelet number	64.63**	0.71	12.18**	2.53*	0.78	5.31
	Grain number per spike	1395.36**	3.85	215.82**	121.79**	1.56	2.93
	Plant height	4570.80**	6.59	303.74**	44.85**	1.68	1.73
	Leaf number per plant	0.48^{ns}	0.17	0.35**	0.64*	0.083	6.62
	Number of days to flowering	85.33^{ns}	85.33	762.19**	2.04^{ns}	6.33	1.86
	Number of days to flowering	2649.24**	0.79	70.07**	29.66**	1.79	3.47
	Degree of freedom	1	4	7	7	28	
	Awn length	9.46^{ns}	1.26	20.78**	0.43^{ns}	0.302	7.92
	Spike length	7.25^{ns}	1.12	18.36**	0.75^{ns}	0.54	6.85
	Flag leaf length	16.21^{ns}	2.31	21.55**	4.31**	0.85	4.04
	Peduncle length	697.07**	4.79	90**	14.94**	0.87	3.45
	Grain yield per spike	12.66**	0.001	0.123**	0.177**	0.004	4
	Grain yield per plant	757.87**	0.39	27.98**	10.59**	0.32	5.53
	Grain yield	30370.66**	46.71	1243.53**	491.57**	51.71	10.6

ns: not significant; * and **: significant at 5% and 1% probability levels, respectively.

Table 3. Interaction slicing analysis for comparing cultivars across different traits within each condition (cultivation method)

Cultivar name	Aftab	Karim	Dehdasht	Chamran	Mehregan	Saverz	Ghabous	Koohdasht
Tiller number per plant (irrigation)	8.66^{c}	7.56^{d}	7.66^{d}	9.26^{bc}	10.33^{a}	9.53^{abc}	8.63^{c}	9.80^{ab}
Tiller number per plant (drought)	8.33^{ab}	7.33^{c}	6.30^{d}	8.73^{a}	8.73^{a}	7.63b^{c}	8.46a^{b}	8.66^{a}
Fertile tiller number per plant (irrigation)	6.96^{bc}	6.03^{d}	4.23^{e}	6.93^{c}	7.30^{bc}	5.80^{d}	7.76^{ab}	8.33^{a}
Fertile tiller number per plant (drought)	6.86^{b}	3.76^{e}	3.00^{f}	4.73^{d}	6.30^{c}	5.06^{d}	4.83^{d}	7.36^{a}
Spikelet number (irrigation)	19.40^{ab}	17.86^{c}	15.53^{d}	19.80^{a}	18.33b^{c}	16.56^{d}	19.20a^{b}	15.93^{d}
Spikelet number (drought)	15.06^{bc}	16.06^{ab}	13.26^{c}	16.26^{ab}	16.46^{ab}	13.53^{c}	17.60^{a}	15.80^{ab}
Grain number per spike (irrigation)	50.20c	45.26d	43.26d	63.66a	53.00b	37.40e	48.60c	44.53d
Grain number per spike (drought)	39.20bc	28.20d	26.33d	40.66b	37.06c	37.26c	44.66a	44.26a
Flag leaf length (cm) (irrigation)	83.66^{d}	88.24^{c}	75.98^{f}	78.26^{e}	83.60^{d}	83.40^{d}	93.80^{a}	91.30^{b}
Flag leaf length (cm) (drought)	68.90^{c}	59.82^{e}	48.56^{f}	63.46^{d}	65.46^{d}	65.03^{d}	78.70^{a}	72.16^{b}
Peduncle length (cm) (irrigation)	5.23^{a}	4.36b^{c}	4.03^{cd}	4.50^{b}	3.83^{d}	4.20b^{cd}	4.00^{cd}	4.00^{cd}
Peduncle length (cm) (drought)	4.00^{c}	5.00^{a}	4.33^{abc}	4.83^{ab}	4.80^{ab}	4.10^{c}	4.40^{abc}	4.30^{bc}
Thousand-kernel weight (g) (irrigation)	46.0^{b}	47.6^{b}	52.7^{a}	41.2^{c}	42.5^{c}	53.6^{a}	39.0^{d}	41.90^{c}
Thousand-kernel weight (g) (drought)	29.3^{bc}	31.1^{ab}	32.1^{ab}	32.0^{ab}	30.3^{b}	33.7^{a}	30.1^{b}	27.1^{c}
Flag leaf length (cm) (irrigation)	21.43^{cde}	20.40^{e}	23.03^{bc}	20.87^{de}	22.46^{bcd}	20.41^{e}	23.78^{b}	26.23^{a}
Flag leaf length (cm) (drought)	20.52^{d}	24.45^{b}	24.06^{b}	22.28^{c}	24.40^{b}	22.17^{c}	22.41^{c}	27.60^{a}
Peduncle length (cm) (irrigation)	28.2^{e}	30.4^{cd}	29.1d^{e}	24.6f	32.2bc	31.4c	33.8b	37.1a
Peduncle length (cm) (drought)	25.1^{c}	20.8^{d}	17.4^{e}	18.6^{e}	24.4^{c}	21.1^{d}	30.2^{a}	28.3^{b}
Grain yield per spike (g) (irrigation)	2.31^{b}	2.15^{c}	2.28^{b}	2.62^{a}	2.25^{bc}	1.95^{d}	1.90^{d}	1.87^{d}
Grain yield per spike (g) (drought)	1.15bc	0.87d	0.84d	1.30a	1.12c	1.25ab	1.34a	1.23abc
Grain yield per plant (g) (irrigation)	15.54b	13.22c	9.93 e	17.19a	16.96a	11.70d	15.12b	13.85c
Grain yield per plant (g) (drought)	7.60^{b}	3.33^{e}	2.62^{e}	6.03^{d}	7.23b^{c}	6.30c^{d}	6.04^{d}	10.80^{a}
Grain yield (kg/ha) (irrigation)	3315.8^{ab}	2770.6^{cd}	2057.8^{e}	3589.7^{a}	3539.1^{a}	2365.4^{de}	3027.0^{bc}	2842.4^{bc}
Grain yield (kg/ha) (drought)	1509.9^{b}	714.3^{c}	562.6^{c}	1388.3^{b}	1526.5^{b}	1397.7^{b}	1390.5^{b}	2291.2^{a}

In each row, means with the same letter are not statistically significant (LSmeans; $P < 0.05$).

Table 4. Heatmap of correlation coefficients among various traits evaluated under irrigated conditions

	TN/P	FNT/P	SN	GN/S	PH	NL/P	DF	TKW	AL	SL	FLL	PL	GY/S	GY/P	GY
TN/P	1														
FNT/P	0.698**	1													
SN	0.172^{ns}	0.473 ^{ns}	1												
GN/S	0.294 ^{ns}	0.440 ^{ns}	0.783**	1											
PH	0.222 ^{ns}	0.765**	0.203 ^{ns}	-0.314	1										
NL/P	-0.368 ^{ns}	-0.130 ^{ns}	0.387 ^{ns}	0.307	-0.312 ^{ns}	1									
DF	0.188 ^{ns}	0.127 ^{ns}	-0.221 ^{ns}	0.540*	-0.367 ^{ns}	-0.330 ^{ns}	1								
TKW	-0.442 ^{ns}	-0.891**	-0.651**	-0.775**	-0.585*	0.181 ^{ns}	-0.293 ^{ns}	1							
AL	-0.369 ^{ns}	-0.885**	-0.571*	-0.693**	-0.640**	0.148 ^{ns}	-0.344 ^{ns}	0.890**	1						
SL	0.381 ^{ns}	0.816**	0.626**	0.670**	0.489 ^{ns}	0.363 ^{ns}	0.267 ^{ns}	-0.841**	-0.839**	1					
FLL	0.383 ^{ns}	0.520*	-0.400 ^{ns}	-0.200	0.511*	-0.508*	0.213 ^{ns}	-0.514*	-0.407 ^{ns}	0.412 ^{ns}	1				
PL	0.386 ^{ns}	0.531*	-0.490 ^{ns}	-0.599*	0.853**	-0.672**	-0.263 ^{ns}	-0.300 ^{ns}	-0.348 ^{ns}	0.214 ^{ns}	0.771**	1			
GY/S	-0.183 ^{ns}	-0.352 ^{ns}	0.518*	0.841**	-0.813**	0.471 ^{ns}	0.520*	-0.113 ^{ns}	-0.131 ^{ns}	0.243 ^{ns}	-0.586*	-0.842**	1		
GY/P	0.591*	0.792**	0.840**	0.863**	0.284 ^{ns}	0.331 ^{ns}	0.214 ^{ns}	-0.785**	-0.802**	0.753**	-0.197 ^{ns}	-0.275 ^{ns}	0.515*	1	
GY	0.570*	0.768**	0.816**	0.872**	0.259 ^{ns}	0.307 ^{ns}	0.264 ^{ns}	-0.776**	-0.812**	0.755**	-0.170 ^{ns}	-0.276 ^{ns}	0.538*	0.978**	1

Tiller number per plant (TN/P), Fertile tiller number per plant (FTN/P), Spikelet number (SN), Grain number per spike (GN/S), Plant height **(PH),** Leaf number per plant (LN/P), Number of days to flowering (DF), Thousand-kernel weight (TKW), Awn length (AL), Spike length (SL), Flag leaf length (FLL), Peduncle length (PL), Grain yield per spike (GY/S), Grain yield per plant (GY/P), Grain yield (GY)

ns: not significant; * and **: significant at 5% and 1% probability levels, respectively.

Table 5. Heatmap of correlation coefficients among various traits evaluated under drought stress conditions

	TN/P	FTN/P	SN	GN/S	PH	NL/P	DF	TKW	AL	SL	FLL	PL	GY/S	GY/P	GY
TN/P	1														
FTN/P	0.798**	1													
SN	0.748**	0.357 ^{ns}	1												
GN/S	0.869**	0.818**	0.581*	1											
PH	0.828**	0.752**	0.725**	0.878**	1										
NL/P	0.208 ^{ns}	-0.376 ^{ns}	0.416 ^{ns}	-0.299 ^{ns}	-0.259 ^{ns}	1									
DF	0.119 ^{ns}	-0.266 ^{ns}	0. 197 ^{ns}	-0.250 ^{ns}	-0.412 ^{ns}	0.616**	1								
TKW	-0.466 ^{ns}	-0.691**	-0.313 ^{ns}	-0.544*	-0.518*	0.200 ^{ns}	-0.136 ^{ns}	1							
AL	-0.731**	-0.538*	-0.724**	-0.568*	-0.560*	-0.423 ^{ns}	-0.344 ^{ns}	0.755**	1						
SL	0.756**	0.671**	0.763**	0.751**	0.728**	0.217 ^{ns}	0.240 ^{ns}	-0.771**	-0.874**	1					
FLL	0.136 ^{ns}	0.262 ^{ns}	0.210 ^{ns}	0.108 ^{ns}	-0.151	0.264 ^{ns}	0.648**	-0.503*	-0.214 ^{ns}	0.298 ^{ns}	1				
PL	0.668**	0.740**	0.657**	0.825**	0.895**	-0.274 ^{ns}	-0.424 ^{ns}	-0.662**	-0.547*	0.675**	0.276 ^{ns}	1			
GY/S	0. 792**	0.614**	0.542*	0.905**	0.883**	-0.252 ^{ns}	-0.297 ^{ns}	-0.127 ^{ns}	-0.331 ^{ns}	0.516*	-0.314 ^{ns}	0.633**	1		
GY/P	0.839**	0.895**	0.497 ^{ns}	0.848**	0.818**	-0.288 ^{ns}	-0.137 ^{ns}	-0.563*	-0.458 ^{ns}	0.691**	0.369 ^{ns}	0.763**	0.813**	1	
GY	0.845**	0.874**	0.481 ^{ns}	0.848**	0.820**	-0.281 ^{ns}	-0.126 ^{ns}	-0.560*	-0.436 ^{ns}	0.671**	0.390 ^{ns}	0.760**	0.813**	0.992**	1

Tiller number per plant (TN/P), Fertile tiller number per plant (FTN/P), Spikelet number (SN), Grain number per spike (GN/S), Plant height **(PH),** Leaf number per plant (LN/P), Number of days to flowering (DF), Thousand-kernel weight (TKW), Awn length (AL), Spike length (SL), Flag leaf length (FLL), Peduncle length (PL), Grain yield per spike (GY/S), Grain yield per plant (GY/P), Grain yield (GY)

ns: not significant; * and **: significant at 5% and 1% probability levels, respectively.

Comparison of correlation coefficients between the two conditions revealed that the correlations between different wheat traits were significantly different under drought stress and irrigated conditions. In drought stress conditions (unlike irrigated conditions), there was a significant correlation between the following traits: tiller number per plant and spikelet number, plant height and tiller number per plant, plant height and spikelet number, plant height and grain number per spike, awn length and tiller number per plant, spike length and tiller number per plant, spike length and plant height, flag leaf length and number of days to flowering, and peduncle length and spikelet number. Under stress, the overall plant growth is reduced and the plant redirects its resources towards water uptake by the roots. This not only affects various traits but also alters the correlations between them. Water stress also affects gene expression. In irrigated conditions (unlike drought stress), there was a significant correlation between the following traits: number of days to flowering and grain number per spike, thousand-kernel weight and spikelet number, flag leaf length and plant height, and flag leaf length and leaf number per plant. These differences suggest that the growth condition can influence the relationships between various traits in wheat. Divergent correlation patterns across environments highlight the influence of the drought stress on the phenotypic covariance structure. This implies that gene expression for different traits can vary under different environmental conditions (Nezhadahmadi *et al*., 2013). Consequently, in breeding programs and cultivar selection, environmental variability should be considered.

Factor analysis

The adequacy and sufficiency of the correlation matrix for factor analysis were assessed using Bartlett's test of sphericity (Table 6). Since the hypothesis that the correlation matrix is equal to 1 was rejected (indicating significant correlations between at least a few variables), it was evident that the correlation matrix had significant correlations. Given the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy of 0.683, factor analysis was deemed suitable for the data (Napitupulu *et al*., 2017).

The significance of Bartlett's test of sphericity (Table 6) indicated that there were significant correlations among the variables, justifying the application of factor analysis (Shrestha, 2021).

Based on the eigenvalues greater than 1 (Table 7), four factors were identified as the most significant contributors to explaining the variance in the data. These four factors collectively explained 76.98% of the total variance (Table 8).

The commonality, which represents the proportion of variance of each variable explained by the common factors, was high for all traits (Table 7). This indicates that the chosen number of factors was able to effectively represent the variations in the traits. According to Table 7, the traits related to yield and its components were more strongly influenced by the extracted factors. The factor loadings were rotated using the Varimax method (Table 7). Factor 1 was associated with thousand-kernel weight, awn length (negative effect), spike length, yield traits, fertile tiller number per plant, grain number per spike, and spikelet number. This factor could be termed agronomic and yield potential. Selecting cultivars based on this factor could lead to improved yields. Based on this factor, the Chamran cultivar showed high yield potential under irrigated conditions. Factor 2 was associated with the fertile tiller number per plant (negatively), grain number per spike, spikelet number, peduncle length (negatively), grain yield per plant, plant height (negatively), flag leaf length, and leaf number per plant. Selecting cultivars based on this factor could lead to improved yields. The Aftab cultivar demonstrated favorable grain yield based on this factor. The highest loading for factor 3 was associated with the number of days to flowering. The underlying factor here can be termed phenology. In factor 4, the highest loading was associated with the tiller number per plant. However, this factor was also associated with the leaf number per plant (negatively), grain yield per hectare, and grain yield per plant. Based on this factor, the Mehrgan cultivar exhibited a favorable position in relation to the traits associated with this factor.

In statistics, factor analysis is a method to reduce the complexity of data by identifying a few latent factors that explain the variance in multiple dependent variables (Chatfield, 2018). The purpose of factor analysis is to simplify the description of complex data by reducing the number of variables (Backhaus et al, 2021). Simple correlations alone are not capable of providing a comprehensive representation of the relationships between different traits, especially when they are related to plant performance (Mardia *et al*., 2024). The complexity of these relationships necessitates the use of multivariate statistical methods, such as factor analysis, to gain a deeper understanding of these interactions (Backhaus *et al*., 2021). Employing Varimax rotation in factor analysis maximizes the variance between factors. In this approach, factors that account for a higher proportion of the variation among traits are considered more important and can be utilized as key criteria in plant breeding programs. Assigning specific names to factors in factor analysis provides a roadmap for more precise and targeted plant breeding, emphasizing the determinant factors that impact performance (Filipović *et al*., 2014).

Factor analysis for drought stress conditions

According to the KMO measure of sampling adequacy (0.697), factor analysis was deemed appropriate for the data (Napitupulu *et al*., 2017). Bartlett's sphericity test was significant (Table 9). This implies that there was a significant correlation among the variables, and factor analysis was permissible (Shrestha, 2021).

Table 6. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (irrigated conditions)

Property	Amount
Kaiser-Meyer-Olkin measure of sampling adequacy	0.683
Bartlett's test of sphericity	
Chi-square approximation	458.677
Degrees of freedom	105
Significance level	0.000

Table 7. Factor analysis based on principal components using Varimax rotation for different traits of wheat genotypes under irrigated conditions

Traits	Communality	First factor	Second factor	Third factor	Fourth factor
Thousand-kernel weight	0.899	-0.894	-0.243	-0.193	-0.052
Awn length	0.890	-0.891	-0.252	-0.180	-0.002
Spike length	0.777	0.868	0.117	0.064	-0.076
Grain yield per plant	0.960	0.865	-0.267	-0.091	0.363
Grain yield	0.933	0.859	-0.270	- 0.030	0.348
Fertile tiller number per plant	0.916	0.789	-0.425	-0.079	0.299
Grain number per spike	0.951	0.750	0.515	0.346	0.058
Spikelet number	0.777	0.734	0.394	-0.287	-0.003
Peduncle length	0.943	-0.007	-0.954	0.299	0.179
Grain yield per spike	0.956	0.227	0.902	-0.098	-0.020
Plant height	0.896	0.421	-0.791	-0.298	-0.066
Flag leaf length	0.720	0.157	-0.739	0.382	0.052
Leaf number per plant	0.661	0.230	0.506	-0.450	-0.387
Number of days to flowering	0.846	0.140	-0.172	0.892	0.019
Tiller number per plant	0.923	0.275	0.154	0.058	0.904
Eigenvalues		6.21	4.15	1.64	1.03
Partial variance (%)		41.40	17.71	10.98	6.89
Cumulative variance (%)		41.40	59.11	70.09	76.98

Table 8. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (drought stress conditions)

Property	Amount
Kaiser-Meyer-Olkin measure of sampling adequacy	0.697
Bartlett's test of sphericity	
Chi-square approximation	468.53
Degrees of freedom	105
Significance level	0.00

Based on the eigenvalues greater than 1 (Table 9), four factors were identified as the most significant factors that explained the highest variance in the data. These four factors together explained 86.30% of the total variance (Table 9). Factor loadings were rotated using the Varimax method (Table 9). Factor 1 was associated with traits such as yield, plant height, tiller number per plant, fertile tiller number per plant, peduncle and spike length, and spikelet number. This factor is associated with plant production. Under drought stress cultivation conditions, the Koohdasht and Ghabous cultivars showed the highest adaptation to this factor. Similarly, in a study of 97 wheat genotypes in Hungary, Bányai *et al*. (2020) identified similar traits associated with yield under both drought stress and irrigated conditions using PCA. Factor 2 was associated with plant height, fertile tiller number per plant, peduncle length, thousand-kernel weight (negatively), awn length (negatively), and spike length. This factor placed greater emphasis on plant structure. In a study by Arduini *et al*. (2018), varieties capable of producing a greater fertile tiller number per plant under stressful conditions helped to compensate the main stem yield. Under drought stress conditions, genotypes with taller plant height and longer peduncle length are preferred for increased production and transport of nutrients to the spike (Moetamadipoor *et al*., 2015). The traits of the number of days to flowering, spikelet number, leaf number per plant, spike length, awn length, and tiller number per plant were associated with factor 3. This factor placed a greater emphasis on traits related to reproductive growth. In factor 4, flag leaf length and number of days to flowering (phenology) were more important.

CONCLUSION

The results of the experiment revealed diversity among wheat genotypes in how various wheat traits responded to drought stress conditions. The results of this study showed that the correlations between different wheat traits were significantly different in the two irrigated and drought stress conditions. These differences could be due to the effect of stress on gene expression, leading to changes in trait relationships. Yield components such as the tiller number per plant, spikelet number, and grain number per spike showed positive correlations with grain yield in both conditions. This suggests that selecting cultivars with higher values of these traits could lead to increased grain yield under both irrigated and drought stress conditions. Substantially, this study revealed that water stress had a significant impact on trait correlations and wheat yield.

Table 9. Factor analysis based on principal components using Varimax rotation for different traits of wheat cultivars under drought stress conditions

Traits	Communality	First factor	Second factor	Third factor	Fourth factor
Yield	0.970	0.931	-0.240	-0.053	0.206
Grain yield per plant	0.965	0.927	-0.256	-0.045	-0.188
Grain number per spike	0.901	0.906	-0.248	0.137	-0.129
Grain yield per spike	0.933	0.899	0.155	0.184	-0.260
Plant height	0.918	0.788	-0.299	0.214	-0.295
Tiller number per plant	0.825	0.768	-0.218	0.429	-0.012
Fertile tiller number per plant	0.836	0.768	0.465	-0.147	0.089
Peduncle length	0.770	0.630	0.568	0.081	-0.215
Thousand-kernel weight	0.931	-0.210	-0.921	0.007	-0.195
Awn length	0.868	-0.224	-0.640	-0.636	-0.054
Spike length	0.822	0.467	0.623	0.461	0.068
Leaf number per plant	0.767	-0.224	0.153	0.768	0.278
Spikelet number	0.774	0.410	-0.241	0.731	-0.091
Flag leaf length	0.803	0.070	-0.297	-0.066	0.842
Number of days to flowering	0.866	-0.125	0.121	0.406	0.819
Eigenvalues	-	7.75	2.44	1.56	1.17
Partial variance (%)	-	51.73	16.31	10.42	7.84
Cumulative variance (%)	-	51.73	68.04	74.46	86.30

Selecting appropriate cultivars based on cultivation conditions can contribute to increased grain yield and improved yield stability under water stress. In both cultivation conditions and based on factor analysis, spike and plant yield indices, yield components (spike length, spikelet number, and fertile tiller number per plant), and plant height exhibited the highest commonality and, consequently, the greatest relative contribution to grain yield. In other words, yield-related morphometric traits were the primary determinants of the agronomic and yield potential of the studied wheat cultivars under both cultivation conditions. These traits can be considered as breeding criteria. Among the studied cultivars, Chamran was identified as the most suitable for irrigated cultivation in the Dashtestan County, Bushehr province, Iran. In addition to drought tolerance and good yield, the Kohdasht cultivar also exhibited yield stability under irrigated conditions.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization: Hamidreza Nooryazdan; Methodology: Hamidreza Nooryazdan; Software: Hamidreza Nooryazdan; Validation: Hamidreza Nooryazdan; Formal analysis: Hamidreza Nooryazdan; Investigation: Hamidreza Nooryazdan; Resources: Hamidreza Nooryazdan; Data curation: Hamidreza Nooryazdan; Writing—original draft preparation: Hamidreza Nooryazdan; Writing—review and editing: Hamidreza Nooryazdan; Visualization: Hamidreza Nooryazdan; Supervision: Hamidreza Nooryazdan; Project administration: Hamidreza Nooryazdan; Funding acquisition: Hamidreza Nooryazdan.

DECLARATION OF COMPETING INTEREST

The author declares no conflict of interest.

ETHICAL STATEMENT

None.

DATA AVAILABILITY

All relevant data will be made available from the author on request.

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