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Genetic Diversity among Wheat Advanced Lines Using Different Stress Indices

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Abstract

Drought is a primary constraint influencing wheat production and quality. This study evaluated 30 wheat genotypes under irrigated and rainfed conditions at the University of Agriculture, Peshawar, Pakistan (2022-23), using a randomized complete block design with three replications. Combined analysis of variance revealed significant ($P \leq 0.01$) differences between environments for all traits except grains spike^{-1} and grain weight spike^{-1}. Significant genetic variation ($P \leq 0.01$) was observed among genotypes for most traits, excluding spikes m^{-2}, grains spike^{-1}, grain weight spike^{-1}, and biological yield. Genotype × environment (G×E) interactions were highly significant ($P \leq 0.01$) for all traits except grain weight spike^{-1} and grain yield. Drought stress reduced mean performance across genotypes for: spikes m^{-2} (481 to 378), spike length (12.0 to 10.7 cm), spikelets spike^{-1} (24 to 20), grains spike^{-1} (74 to 72), grain weight spike^{-1} (2.4 to 1.9 g), 1000-grain weight (44 to 39 g), biological yield (8789 to 7320 kg ha^{-1}), grain yield (3705 to 2508 kg ha^{-1}), and harvest index (42 to 35%). Heritability and expected genetic advance for key traits, including grain yield and 1000-grain weight, were higher under irrigated conditions. Grain yield showed a significant positive genotypic (r_g) and phenotypic (r_p) correlation with plant height in both irrigated (r_g=0.687; r_p=0.472) and rainfed (r_g=0.471; r_p=0.347) environments. Superior grain yield was recorded for G-4 (4748 kg ha^{-1}), G-22 (4500 kg ha^{-1}), and G-12 (4389 kg ha^{-1}) under irrigation, and G-10 (3489 kg ha^{-1}), G-22 (3408 kg ha^{-1}), and G-6 (3056 kg ha^{-1}) under rainfed conditions. Based on stress selection indices, genotype G-13 (TOL=111.1, YSI=0.99, SSI=0.09) and G-17 (MP=9111, STI=1.07) were identified as superior for biological yield, while G-22 (MP=3954, STI=1.11) and G-30 (TOL=110.4, YSI=224.3, SSI=0.40) excelled for grain yield stability and tolerance. Selection indices such as TOL, MP, YSI, SSI, and STI proved to be effective indicators for identifying drought-tolerant wheat genotypes.

Keywords: *Triticum aestivum* L.; Drought stress; Genetic variation; Heritability; Selection indices; Grain yield; G×E interaction; Rainfed conditions.

INTRODUCTION

Wheat (*Triticum aestivum L.*) is widely cultivated worldwide and is the staple food of most of the world population. There are three important species of wheat: i) Diploid (2n=14), ii) tetraploid (2n=28) and iii) hexaploid (2n=42). Flour is the important produce of wheat grain from which other kind of food products like nans, pastries, chapattis and roti are made. Wheat straw is the important source of animal's feed. Wheat usually takes 140-170 days from planting till harvest, depending upon soil, quality of the seeds and climatic conditions. Globally 36% of the population directly depends on wheat (Giraldo *et al.*, 2019).

Wheat is grown on around one-sixth of the world's agricultural land. Wheat production has increased in many parts of the world since the green revolution (Mwadzingeni *et al.,* 2017). Worldwide, wheat production during 2022-23 was 790.59 million tons from an area of 220.51 million hectares and average grain yield was 3.58 tons ha^{-1} (USDA, 2023). In Pakistan wheat is grown in both irrigated and rainfed regions. Wheat was yielding a total of 26.8 million tons in Pakistan during 2022-23, with an average yield of 2980 kg ha^{-1}. Similarly, 1.6 million tons wheat was produced in Khyber Pakhtunkhwa from an area of 0.8 million hectares with an average yield of 2000 kg ha^{-1}. Most of the wheat production of Pakistan comes from Punjab 20.5 million tons from an area of 6.6 million hectares and the average grain yield was 3110 kg ha^{-1}. Sindh, 4.1 million tons from an area of 1.2 million hectares and the average grain yield was 3420 kg ha^{-1}. Baluchistan, 0.9 million tons from an area of 0.4 million hectares and the average grain yield was 2250 kg ha^{-1}. Most of the wheat production of Pakistan comes from Punjab (76%) followed by Sindh (15%), Khyber Pakhtunkhwa (6%) and Baluchistan for (3%). PBS, (2022-23).

The major reasons for lower yield of wheat in Pakistan are poor quality seed, poor seedbed preparation and low moisture availability during critical stages. There are many factors behind this lower yield, however drought is one of the known major yield-limiting factors in wheat (Nazir *et al*., 2019). In recent years, drought severity is being adversed by the current climatic change. Globally, drought usually prevails in the semi-arid and arid regions. In response to water deficit, morphological and biochemical changes are witnessed in plants which follow functional damage and loss of yield (Arif *et al.,* 2020). There are various ways in which drought-tolerant wheat species can be differentiated. These include growth response in water-limited conditions, alteration in water relations in tissues subjected to water stress, and early flowering (Rashid *et al.,* 2021).

Considerable improvement in wheat yield is still possible through use of genetically superior cultivars and optimum production technology. Water resources are steadily depleting because of the increase in water demand by growing human population and water consumption by domestic, environmental, and industrial sectors. As a result, the optimum provision of water to agricultural crops will decrease in near future. Indeed, agricultural crops are currently facing severe water shortages (Chowdhury *et al*., 2021) and reduction in global water availability has caused at least a 20.6% reduction in bread wheat yield within the last 40 years (Daryanto *et al.,* 2016). Thus, use of high yielding genotypes having drought tolerance is an effective approach to reduce drought damaging effects. One of the basic strategies to overcome problems caused by drought is selecting resistant cultivars and their use in breeding programs (Anwaar *et al.,* 2020).

Owing to global climate changes, wheat yields are expected to decline by 6% for each 1Cº increase in temperature. Therefore, gain yield of wheat crop must be increased by 60% until 2050 to fulfil the food demands of increasing global population (Asseng *et al*., 2015). Temperatures below or above normal alter plant function and productivity. Germination is a critical process, as temperature below 12ºC result in poor and uneven emergence. Poor crop establishment results in few tillers and finally decreased grain yield (Farooq *et al.,* 2008). Subsequently short period of high temperature stress i.e. 35ºC at reproductive stage like grain filling decrease the grain weight (Wardlaw and Wrigley, 1994) and reduce the grain quality in wheat (Randall and Moss, 1990). High temperature also enhances leaf senescence causing reduction in green leaf area during reproductive stages. The rapid leaf senescence ultimately results in fewer spikes $plant^{-1}$ which is one of the major causes of yield loss of wheat. Generally, wheat like other cool season crop is seeded early to take maximum period for growth and development towards maturity before the possible heat stress. The crop may be exposed to more thermal stress in the near future, as it is predicted that the global warming may cause a temperature increase of about 2ºC by the middle of 21st century.

Genetic increase in yield under less favourable and drought prone environments has been recognized to be a difficult challenge for plant breeders, while progress in grain yield has been much higher in favourable environments (Richards et al., 2002). Drought indices which provide a measure of drought based on yield loss under drought condition in comparison to normal conditions have been used for screening drought tolerant genotypes (Mitra, 2001). These indices are either based on drought resistance or susceptibility of genotypes (Fernandez, 1992). Drought resistance is defined by Hall (1993) as the relative yield of a genotype compared to other genotypes subjected to the same drought stress. In contrast, drought susceptibility of a genotype is often measured as a function of the reduction in yield under drought stress (Blum, 1998). Rosielle and Hamblin (1981) defined stress tolerance (TOL) as the difference in yield between stress and non-stress environments and mean productivity (MP) as the average yield of stress and non-stress environments. Fisher and Maurer (1978) proposed a stress susceptibility index (SSI) of the cultivar. Fernandez (1992) defined a new advanced index stress tolerance index (STI), which is used to identify genotypes that produce high yield under both stress and non-stress conditions.

Broad sense heritability is the ratio of genotypic variance to phenotypic variance of the trait. Therefore, heritability is the combined result of genetic architecture population and environmental condition. Heritability is widely used as selection criteria in breeding programs and formation of selection indexes (Falconer, 1985). It provides an estimate of genetic advance a breeder can expect from selection in a population in a given experiment and is essential for an effective crop breeding programme by predicting the behavior of succeeding generation by devising the appropriate selection criteria and assessing the level of genetic improvement. Higher estimate of heritability, simpler the selection procedure (Khan *et al*., 2011). However, estimate of heritability alone do not provide an idea about next generation, unless considered in conjunction with estimates of selection response or genetic advance. The utility of heritability, therefore, increases when used to calculate selection response, which indicates the degree of gain in a character obtained under particular selection pressure.

Genetic advance is the enhancement in the mean phenotypic value of the selected genotypes over the parental population. Genetic advance provides knowledge about the expected gain resulting from selection of superior individuals. Genetic advance gives clear and precise view of segregating generations for possible selection. Since the expected gain is the function of heritability, high heritability coupled with high selection response is desired for effective selection (Paroda and Joshi, 1970).

Correlation analysis is used as an important tool to know about relationship between yield and yield related components (Khan *et al.,* 2011). Effective selection relies on the knowledge of genetic association between grain yield and its components to help breeders to improve the trait of interest. Thus, it is important to study the relationships among the traits and to find their direct and indirect effects on grain yield (Bilgin *et al.,* 2011). Interaction among any two traits is important for effective selection (Ahmad *et al*., 2003). The correlation coefficent between yield and yield components generally demonstrates a compound sequence of interacting association.

The present investigation was conceived to address critical gaps in our understanding of wheat performance across divergent moisture regimes. Our approach encompassed four complementary analyses: first, we characterized the magnitude and patterns of genotype-by-environment interactions for agronomically important traits; second, we quantified the genetic variance components and predicted response to selection under both water-sufficient and water-limited conditions; third, we explored the genetic architecture underlying trait associations through correlation analysis in each environment; and fourth, we employed stress-based selection indices to rank genotypes according to their adaptive capacity. Together, these analyses provide a comprehensive framework for understanding wheat adaptation and informing variety development for regions experiencing variable water availability.

MATERIALS AND METHODS

The present study was carried out at the Research Farm of the Department of Plant Breeding and Genetics, The University of Agriculture, Peshawar, during Rabi growing season 2022-23. Thirty wheat genotypes received from CIMMYT were evaluated in a randomized complete block design with three replications as independent experiments under irrigated and rainfed conditions (Table 1). These genotypes have been obtained from CIMMYT, Mexico, under the National Wheat Co-ordinated Programme of NARC, Islamabad. The rainfed experiment was not irrigated throughout the cropping season to simulate rainfed conditions. Each genotype was assigned to a 4-row plot, 3 m long, with 25 cm between rows. Both experiments were planted during the 2nd week of Nov, 2022. Data was recorded on days to heading, flag leaf area, days to maturity, plant height, spikes m^{-2}, spike length, spikelets $spike^{-1}$, grains $spike^{-1}$, grain weight $spike^{-1}$, thousand grain weight, grain yield, biological yield, and harvest index. Cultural practices and inputs, such as irrigation, weed management, and fertilizer, were uniformly applied to both experiments.

Table A: List of CIMMYT wheat genotypes evaluated at the University of Agriculture, Peshawar during 2022-23

S. No	Genotypes	S. No	Genotypes	S. No	Genotypes
1	G-01	13	G-13	25	G-25
2	G-02	14	G-14	26	G-26
3	G-03	15	G-15	27	G-27
4	G-04	16	G-16	28	G-28
5	G-05	17	G-17	29	G-29
6	G-06	18	G-18	30	G-30
7	G-07	19	G-19		
8	G-08	20	G-20		
9	G-09	21	G-21		
10	G-10	22	G-22		
11	G-11	23	G-23		
12	G-12	24	G-24		

Statistical Analysis

Data were analyzed across irrigated and rainfed condition (Table 2) for each trait. So, genotype × environment interaction was significant for most of the traits, data were analyzed independently for each environment to compute genetic and environmental variances required for estimation of broad sense heritability (Singh and Chaudhery, 1997).

I. Estimation of heritability

Variance components were computed from the ANOVA of each trait both under rainfed and irrigated conditions for the estimation of broad-sense heritability on plot mean basis using the following formulas,

Genetic variance = σ^2_g = (GMS-EMS) / Reps = X_1

Environmental variance = σ^2_e = EMS = X_2

Phenotypic variance = $\sigma^2_p = \sigma^2_g + \sigma^2_e = X_3$

Heritability = $h^2_{(B.S)} = \sigma^2_g / \sigma^2_p = X_1 / X_3$

II. Estimation of Genetic advance

Genetic advance was determined for important yield component traits by using the following formula of Panse and Sukhatme (1967),

GA = i × √(Vp) × h^2

Where,

GA = Expected genetic advance

SI % = Constant at 10% (1.755)

√(Vp) = Phenotypic variance of the trait

h^2_{BS} = Broad sense heritability of a trait

III. Correlation Analysis

Both genetic and phenotypic correlation among the studied traits were computed under each environment (rainfed and irrigated) using the following formulas;

Genetic correlation = $r_g = \sigma_g (x_1 x_2) / \sqrt{[\sigma^2_g (x_1)\, \sigma^2_g (x_2)]}$

Phenotypic correlation = $r_p = \sigma_p (x_1 x_2) / \sqrt{[\sigma^2_p (x_1)\, \sigma^2_p (x_2)]}$

Where,

$\sigma_g (x_1 x_2)$ = Genetic covariance between trait x_1 and x_2 under a specific planting condition

$\sigma_p (x_1 x_2)$ = Phenotypic covariance between trait x_1 and x_2 under a specific planting condition

$\sigma^2_g (x_1)$ = Genetic variance of trait x_1, $\sigma^2_g (x_2)$ = Genetic variance of trait x_2

$\sigma^2_p (x_1)$ = Phenotypic variance of trait x_1, $\sigma^2_p (x_2)$ = Phenotypic variance of trait x_2.

Stress selection indices:

The tolerance index (TOL), mean productivity (MP), stress tolerance index (STI), yield stability index (YSI), and stress susceptibility index (SSI) were computed for assessing the response of wheat genotypes under non-stress (irrigated) and stress (rain-fed) environments.

Tolerance Index

Tolerance index was calculated according to formula suggested by Rosielle and Hambling (1981).

TOL = Yn –Ys

Mean Productivity

Formula proposed by Rosielle and Hambling (1981), the mean productivity was measured.

$$MP = \frac{Ys+Yn}{2}$$

Stress susceptibility index

The stress susceptibility index was find out using the following formula as suggested by Fischer and Maurer (1978).

SSI=1-(Ys /Yn)/1-(Ȳs/Ȳn)

Yield stability index

Yield stability index for each genotype was measured using the formula recommended by Bouslama and Schapaugh (1984).

YSI= Ys/Yn

Stress tolerance index

The stress tolerance index was computed using formula as proposed by Fernandez (1992).

STI= (YnxYs)/(Ȳn)²

Where;

Yn = Genotype means for that trait under irrigated condition.

Ys = Genotype means for that trait under rain-fed condition.

Ȳn = Grand mean of a specific trait under irrigated condition.

Ȳs = Grand mean of a specific trait under rain-fed condition.

RESULTS AND DISCUSSION

Days to heading

Analysis of variance revealed highly significant ($P \leq 0.01$) effects of environment and genotype × environment (G × E) interactions on days to heading, while genotypic differences were significant at ($P \geq 0.05$) (Table 1). The significant G × E interaction indicates that genotype phenology was differentially influenced by moisture regimes, consistent with prior reports of environmental sensitivity in wheat heading dates (Khan *et al.,* 2011; Ahmad *et al.,* 2011).

Heading duration ranged from 116–123 days under irrigated conditions and 115–121 days under rainfed conditions (Table 2). On average, moisture stress accelerated heading by 3 days. Genotype G-1 was the earliest to head across both irrigated (116 days) and rainfed (115 days) environments. Evaluation of drought indices identified G-27, G-13, and G-24 as highly stress-tolerant, characterized by the lowest stress susceptibility (SSI: 0.00–0.20) and highest stress tolerance indices (STI: 1.00–1.01; Table 2). Following the criteria of Gutteri *et al.,* (2001), these genotypes (SSI < 1.0) demonstrate below-average susceptibility to drought, indicating high potential for stable performance in water-limited environments.

Genetic variance exceeded environmental variance in both moisture regimes (Table 8, Fig. 1). Broad-sense heritability was moderate, recorded at 0.53 (irrigated) and 0.52 (rainfed), with an expected genetic advance (GA) of 1.79 and 1.61, respectively. Combined analysis across environments yielded a heritability of 0.50 and a GA of 1.08 days. These moderate estimates align with observations by Yaqoob (2016) and Ullah *et al.,* (2011), suggesting that while selection for heading date is feasible, it may be influenced by the testing environment.

Correlation analysis showed that days to heading had a highly significant positive genotypic (r_g =0.587**) and phenotypic (r_p = 0.485*) association with 1000-grain weight under irrigated conditions (Tables 17–18; Fig. 3, Fig. 4). In the rainfed environment, heading was positively correlated with harvest index (r_g = 0.352*). While some studies have reported non-significant correlations between phenology and yield components (Khamssi and Najaphay, 2012), the current findings suggest that heading timing significantly influences grain filling and biomass partitioning in this germplasm.

Flag leaf area

Analysis of variance revealed highly significant (P ≤ 0.01) differences across environments, genotypes, and their interaction (G × E) for flag leaf area (Table 1), confirming substantial genetic variability as noted by Ullah *et al.,* (2021). Flag leaf area ranged from 19–24 cm² (mean: 22 cm²) under irrigated conditions to 14–21 cm² (mean: 18 cm²) under rainfed conditions, reflecting a 4 cm² reduction due to moisture stress (Table 3). Genotype G-4 exhibited the maximum area under irrigation, while G-13 maintained the highest area (21 cm²) under rainfed conditions.

Stress indices identified G-13 as exceptionally drought-tolerant, possessing the lowest tolerance (TOL = 0.96) and stress susceptibility (SSI = 0.22) values, alongside the highest yield stability index (YSI = 0.96). In terms of overall performance, G-4 achieved the highest stress tolerance index (STI = 0.97), followed by G-13 (0.96). These results support the use of STI as a reliable metric for identifying high-yielding genotypes under stress (Pireivaltou *et al.,* 2010).

Genetic variance exceeded environmental variance in both environments, with broad-sense heritability estimates of 0.53 (irrigated) and 0.52 (rainfed). The pooled analysis across environments revealed a heritability of 0.62 and a genetic advance of 1.27 cm² (Table 8, Fig. 1), consistent with the high heritability reported by Khan and Hassan (2017). Flag leaf area showed significant positive genotypic correlations with harvest index (rg = 0.375*) under irrigation and with grains per spike (rg = 0.424**) under rainfed conditions (Table 17, Fig. 3). While phenotypic correlations were non-significant, these genotypic associations highlight the importance of flag leaf area in determining yield potential under varying moisture regimes (Iqbal *et al.,* 2017).

Days to maturity

Analysis of variance indicated highly significant (P ≤ 0.01) differences for environments and genotype × environment (G × E) interactions, while genotypic effects were significant (P ≥ 0.05) (Table 1). The significant G × E interaction suggests inconsistent genotype maturity rankings across environments, supporting earlier reports by Khan and Naqvi (2011). Maturity duration ranged from 155–159 days under irrigated conditions and 152–156 days under rainfed conditions (Table 4). Moisture stress reduced the mean maturity period by 3 days (156 vs. 153 days), likely reflecting an adaptive drought-escape response. Genotypes G-26 and G-30 were the latest to mature under irrigation (159 days), whereas G-28 remained the latest under rainfed stress (156 days).

G-28 was identified as highly stable and tolerant, exhibiting the lowest TOL (1.00), highest YSI (0.99), and lowest SSI (0.33). Additionally, G-26, G-28, and G-30 showed the highest STI (1.00) (Table 4), indicating their ability to maintain high yield potential across moisture regimes, consistent with the selection criteria used by Kamrani *et al.,* (2017). Genetic variances exceeded environmental variances in both environments (Table 8, Fig. 1). Broad-sense heritability (h²) was higher under rainfed (0.62) than irrigated conditions (0.54), with corresponding genetic advances of 1.18 and 1.09 days, respectively. The decrease in h² to 0.48 across environments underscores the substantial influence of G × E and environmental variances, aligning with results reported by Iqbal *et al.,* (2017).

Genotypic correlation analysis revealed significant positive associations between maturity and yield components, specifically spikes m⁻² (r_g = 0.403*) and grains spike⁻¹ (r_g = 0.451**) under irrigation; the latter remained highly significant under rainfed conditions (r_g = 0.502**) (Table 17, Fig. 3). Conversely, phenotypic correlations under irrigated conditions were significantly negative for grain yield and harvest index (r_p = -0.594**) and plant height (r_p = -0.372*). Rainfed conditions also showed negative phenotypic associations with spikelets spike⁻¹ (r_p = -0.431**) and 1000-grain weight (r_p = -0.374*) (Table 18, Fig. 4). These negative associations with grain yield corroborate Ali et al. (2007), suggesting that late maturity may be disadvantageous under moisture-limited conditions where heat or terminal drought escape is critical.

Plant height

Analysis of variance revealed highly significant differences (P ≤ 0.01) across environments, genotypes, and their interactions (G × E) for plant height (Table 1), consistent with the findings of Tomar et al. (2019). Plant height ranged from 78–90.3 cm under irrigated conditions and 75–83.7 cm under rainfed stress (Table 5). Moisture stress induced a mean height reduction of 8.4 cm (85.1 cm vs. 76.6 cm), reflecting the physiological impact of water deficit on stem elongation. Genotype G-4 was the tallest under irrigation (90.3 cm), while G-10 exhibited the maximum height under rainfed conditions (83.7 cm).

Selection based on drought tolerance indices identified G-14 as the most stable performer, characterized by the lowest TOL (1.33), highest YSI (0.98), and lowest SSI (0.17). These parameters underscore its resilience under moisture-limited conditions. Furthermore, G-10 (1.05) and G-11 (1.02) attained the highest STI values, indicating their superior yield potential across both environments (Table 5).

Genetic analysis demonstrated that genetic variances outweighed environmental variances in both settings (Table 8, Fig. 1). Broad-sense heritability (h^2) was higher under rainfed conditions (0.72) than irrigated (0.58), with corresponding genetic advances of 2.51 and 3.81 cm, respectively. However, combined analysis across environments showed a reduction in h^2 to 0.46 and a genetic advance of 1.69 cm, primarily due to the significant G × E and environmental variances. These results align with the variability in heritability reported by Ullah *et al.,* (2011) and Gerema (2020).

Correlation analysis showed that plant height was genotypically associated with key productivity traits. Under both irrigated and rainfed conditions, plant height exhibited highly significant positive genotypic correlations with grain yield (r_g = 0.471** and 0.687**, respectively) and harvest index (r_g = 0.447** and 0.779**, respectively) (Table 17, Fig. 3). These associations are consistent with Akram et al. (2008), suggesting that genetic factors favoring plant stature also enhance yield potential in this germplasm. Conversely, phenotypic correlations under irrigated conditions were significantly negative for grains per spike (r_p = -0.350*) and grain yield (r_p = -0.347*). Under rainfed stress, plant height showed negative phenotypic associations with biological yield (r_p = -0.382*), grain yield (r_p = -0.472**), and harvest index (r_p = -0.581**) (Table 18, Fig. 4), indicating that while genetic potential is linked to taller stature, phenotypic expression under stress may face trade-offs with biomass and yield allocation.

Spike m^{-2}

Analysis of variance revealed highly significant differences (P ≤ 0.01) for environments and genotype × environment (G × E) interactions, although differences among wheat genotypes were non-significant (Table 1). The significant G × E interaction suggests that the productivity of spikes m^{-2} was inconsistently expressed across moisture regimes, aligning with the findings of Khan *et al.,* (2011). Spikes m^{-2} ranged from 410–570 under irrigated conditions to 324–445 under rainfed stress (Table 6). Moisture deficit resulted in a substantial mean reduction of 103 spikes m^{-2} (481 vs. 378 m^{-2}). Genotype G-21 produced the maximum number of spikes under irrigation (570 m^{-2}), whereas G-24 was superior under rainfed conditions (445 m^{-2}).

Evaluation of stress tolerance indices identified G-9, G-24, and G-22 as the most stable genotypes. G-9 exhibited the lowest tolerance index (TOL = -13.5), highest yield stability index (YSI = 1.04), and lowest stress susceptibility index (SSI = -0.17) (Table 6). According to Anwar et al. (2020), genotypes with high mean productivity (MP) and low SSI/TOL values are ideal for stress-prone environments. G-21 recorded the highest MP (491 m^{-2}) and stress tolerance index (STI = 1.01) (Table 6), suggesting its relative stability across both normal and water-limited environments (Kutlu and Kinaci, 2010).

Genetic analysis indicated that genetic variances were smaller than environmental variances in both environments (Table 8, Fig. 1). Broad-sense heritability (h^2) was low, recorded at 0.35 under irrigated and 0.23 under rainfed conditions, with corresponding genetic advances of 34.0 and 17.0. Combined analysis across environments yielded a further reduction in h^2 (0.21) and genetic advance (9.8), primarily due to the dominant influence of G × E and environmental variances. These findings are consistent with Mohammadi *et al.,* (2008), who reported low heritability for this trait under varying moisture regimes.

Correlation analysis showed that spikes m^{-2} was genotypically associated with several yield-contributing traits under rainfed conditions, exhibiting highly significant positive correlations with spike length (r_g = 0.672**), grains per spike (r_g = 0.822**), and grain weight per spike (r_g = 0.630**) (Table 17, Fig. 3). Phenotypically, a significant positive association was observed only with spike length (r_p = 0.380*) under rainfed stress (Table 18, Fig. 4). These relationships emphasize the role of spikes m^{-2} as a critical determinant of grain yield under moisture-limited conditions, as previously highlighted by Kashif and Khaliq (2004).

Spike length

Analysis of variance indicated highly significant (P ≤ 0.01) differences across environments, genotypes, and genotype × environment (G × E) interactions for spike length (Table 1). These results, aligning with Sabit et al. (2017), demonstrate that both the genetic potential and environmental conditions significantly influenced spike development. Spike length ranged from 10.0–14.0 cm under irrigated conditions to 9.6–12.3 cm under rainfed stress (Table 5). Moisture deficit resulted in a mean reduction of 1.3 cm (12.0 cm vs. 10.7 cm), indicating that terminal drought restricts spike elongation. Genotypes G-14 and G-22 produced the longest spikes under irrigation (14.0 cm), while G-10 and G-14 were superior under rainfed conditions (12.3 cm).

Selection for drought resilience highlighted genotypes G-11 and G-6 as highly stable, exhibiting the lowest TOL values (-0.23 and -0.16, respectively) and the highest YSI values (both 1.02). According to Noreldin and Mahmoud (2017) and Farshadfar *et al.,* (2012), low TOL and high YSI values are reliable indicators of drought resistance. Genotypes G-11 and G-6 also recorded the lowest SSI values (-0.21 and -0.15), further confirming their stability under stress. Conversely, the highest STI values were recorded for G-14 (1.09) and G-22 (1.09), suggesting these genotypes maintain superior yield potential across varying moisture regimes (Table 7).

Genetic analysis revealed that genetic variances were larger than environmental variances in both environments (Table 8, Fig. 1). Broad-sense heritability (h^2) was moderate and consistent across environments, recorded at 0.52 under irrigation and 0.53 under rainfed conditions, with corresponding genetic advances of 1.14 cm and 0.76 cm. In the combined analysis across environments, h^2 decreased to 0.47 and genetic advance to 0.57 cm due to the increased influence of G × E and environmental variances. These moderate heritability values are consistent with the findings of Mohsin et al. (2009) in wheat.

Correlation analysis showed that spike length was positively associated with spikes m^{-2} under rainfed conditions at both genotypic (r_g = 0.672**) and phenotypic (r_p = 0.380*) levels (Table 17, Fig. 3, 18, Fig.4). However, spike length exhibited non-significant associations with most other traits, a trend also noted by Ahmad et al. (2010). These findings suggest that while spike length contributes to the overall reproductive framework under stress, its direct impact on grain yield may be mediated by other component traits.

Spikelets spike^{-1}

Analysis of variance indicated highly significant differences (P ≤ 0.01) across environments, genotypes, and genotype × environment (G × E) interactions for spikelets spike^{-1} (Table 1), consistent with reports by Khan et al. (2020). Spikelets spike^{-1} ranged from 23–25 under irrigated conditions to 19.2–22.8 under rainfed stress (Table 9). Moisture deficit induced a mean reduction of 4 spikelets per spike (24 vs. 20), reflecting the sensitivity of spikelet differentiation to water stress. Genotype G-7 produced the maximum spikelets under irrigation (25), while G-5 and G-7 were superior under rainfed conditions (23).

Selection for drought resilience identified G-5 and G-7 as the most promising genotypes. G-5 exhibited the lowest tolerance index (TOL=1.97) and stress susceptibility index (SSI=0.58), while genotypes G-4, G-5, and G-6 shared the highest yield stability index (YSI=0.92). Genotype G-5 also recorded the highest stress tolerance index (STI=1.02), suggesting its ability to maintain superior sink capacity across moisture regimes (Table 9).

Genetic analysis showed that genetic variances exceeded environmental variances in both environments (Table 16, Fig. 2). Broad-sense heritability (h^2) for spikelets spike^{-1} was moderate to high, recorded at 0.56 under irrigation and 0.61 under rainfed conditions, with corresponding genetic advances of 0.56 and 1.30. In the combined analysis across environments, h^2 was 0.53 with a genetic advance of 0.62. These findings align with Laghari *et al.,* (2010), who observed low to moderate heritability for spikelets spike^{-1} in wheat.

Correlation analysis revealed significant negative genotypic associations between spikelets per spike and spikes m^{-2} (r_g = -0.372**) under irrigated conditions (Table 17, Fig. 3). Under rainfed stress, spikelets per spike exhibited significant negative genotypic (r_g = -0.533*) and phenotypic (r_p = -0.431**) correlations with days to maturity (Table 18, Fig. 4). These negative associations suggest a potential trade-off between the duration of the reproductive phase and the intensity of spikelet formation under stress. Correlations with other traits were non-significant, indicating that spikelet number is relatively independent of most other analyzed parameters in this germplasm.

Grains spike^{-1}

Statistical analysis revealed a highly significant (P ≤ 0.01) genotype × environment (G × E) interaction for grains spike^{-1}, although differences among wheat genotypes were non-significant (Table 1). The lack of significant genotypic variation aligns with previous findings by Shah et al. (2007). Grains spike^{-1} ranged from 69–78 under irrigated conditions to 64–77 under rainfed stress (Table 9), with moisture deficit inducing a modest mean reduction of 2 grains (74 vs. 72). Genotype G-25 was the most productive under irrigation (78 grains), while G-27 excelled under rainfed conditions (77 grains).

Selection for stress tolerance identified G-24, G-29, and G-16 as robust performers across environments, characterized by high mean productivity (MP) and superior stress tolerance index (STI) values (1.03–1.06). Conversely, G-27 and G-22 demonstrated exceptional stability under stress, exhibiting the lowest TOL (-7.00 and -5.67) and SSI (-2.88 and -2.08) values, as well as the highest yield stability index (YSI) values (1.10 and 1.07, respectively) (Table 10). According to Mardeh et al. (2006), these indices effectively identify drought-tolerant genotypes that maintain consistent performance under moisture-limited conditions.

Genetic analysis indicated that environmental variances and G × E interactions outweighed genetic effects in both environments (Table 16, Fig. 2). Consequently, broad-sense heritability (h^2) was low, estimated at 0.36 under irrigation and 0.20 under rainfed conditions, with corresponding genetic advances of 1.73 and 1.58. Across environments, h^2 dropped to 0.06, underscoring the dominant role of the environment in determining this trait, a result consistent with Dave et al. (2021).

Correlation analysis showed that grains per spike was genotypically associated with phenological and morphological parameters. Under irrigated conditions, it correlated positively with days to maturity (r_g = 0.451**). This association strengthened under rainfed stress (r_g = 0.502**), where grains per spike also exhibited strong positive genotypic correlations with spikes m⁻² (r_g = 0.822**) and flag leaf area (r_g = 0.424*), corroborating the findings of Masood et al. (2014). However, negative genotypic associations were observed with spikelets per spike (r_g = -0.486**) and plant height (r_g = -0.403) under rainfed conditions (Table 17, Fig. 3). Phenotypically, a significant negative correlation was noted with plant height (r_p = -0.350*) under stress (Table 18, Fig. 4). These relationships suggest that while grains per spike is favored by extended maturity and higher tiller density, it may face trade-offs with taller plant stature and spikelet intensity under moisture-limited environments.

Grain weight spike^{-1}

Analysis of variance revealed non-significant differences for grain weight spike^{-1} across environments, genotypes, and genotype × environment (G × E) interactions (Table 1). This lack of significant variation is consistent with the findings of Khan *et al.,* (2012) and indicates a high degree of phenotypic stability or limited genetic diversity for this trait in the studied germplasm. Grain weight spike^{-1} ranged from 2.0–2.8 g under irrigated conditions and 1.1–2.4 g under rainfed stress (Table 11). Moisture deficit resulted in a mean reduction of 0.5 g (2.4 g vs. 1.9 g), reflecting the adverse impact of drought on dry matter accumulation in the grain. Genotype G-28 was the most productive under irrigation (2.8 g), whereas G-23 exhibited the highest weight under rainfed conditions (2.4 g).

Selection for stress resilience identified G-5 and G-23 as superior genotypes. G-5 demonstrated the lowest drought sensitivity, exhibiting the lowest TOL (-0.12) and SSI (-0.27) alongside the highest YSI (1.05). Dorostkar *et al.,* (2015) noted that lower TOL and SSI values are effective criteria for selecting genotypes with high tolerance and yield stability. Furthermore, G-23 attained the highest stress tolerance index (STI = 1.02) and mean productivity (MP = 2.4 g), suggesting its robust performance across varying moisture regimes (Table 11).

Genetic analysis showed that environmental variances exceeded genetic variances in both environments (Table 16, Fig. 2). Broad-sense heritability (*h*²) was low, recorded at 0.13 under irrigation and 0.26 under rainfed conditions, with corresponding genetic advances of 0.06 g and 0.16 g. In the combined analysis across environments, *h*² reached 0.42 with a genetic advance of 0.13 g. These results align with Ullah et al. (2018), who also reported low to moderate heritability for grain weight spike^{-1} in wheat.

Correlation analysis revealed that grain weight spike^{-1} was genotypically associated with other spike characteristics. Under irrigated conditions, it exhibited a highly significant positive genotypic correlation with spike length (r_g = 0.490**). Under rainfed stress, the trait showed significant positive genetic associations with spikes m⁻² (r_g = 0.630**) and grains spike^{-1} (r_g = 0.355*) (Table 17, Fig. 3). However, phenotypic correlations with other traits were non-significant across both environments (Table 18, Fig. 4), a trend similarly observed by Lee *et al.,* (2019). These findings suggest that while grain weight per spike is genetically linked to yield components, its phenotypic expression is heavily influenced by environmental factors, limiting its direct use as a selection criterion.

1000-Grain weight

Analysis of variance revealed highly significant (P ≤ 0.01) differences among environments, genotypes, and genotype × environment (G × E) interactions for 1000-grain weight (Table 1). These results, consistent with Bhutto et al. (2016), underscore the significant impact of both genetic and environmental factors on grain size. 1000-grain weight ranged from 40.2–52.4 g under irrigated conditions to 35.2–44.7 g under rainfed stress (Table 12). Moisture deficit reduced the mean weight by 5 g (44 vs. 39 g), reflecting the physiological constraints imposed by terminal drought on grain filling. Genotype G-18 produced the heaviest grains under irrigation (52.4 g), whereas G-13 maintained the highest weight under rainfed conditions (44.7 g).

Selection for stress resilience identified genotypes G-2 and G-1 as highly stable, exhibiting the lowest TOL (0.70 and 0.93) and SSI (0.13 and 0.17) values, alongside the highest YSI (0.98). These indices indicate superior drought tolerance and minimal reduction in grain weight under stress. Furthermore, G-13 attained the highest mean productivity (47.2 g) and stress tolerance index (STI = 1.12), suggesting its ability to perform robustly across varying moisture regimes (Table 12).

Genetic analysis demonstrated that genetic variances outweighed environmental variances in both settings (Table 16, Fig. 2). Broad-sense heritability (*h*²) was 0.54 under both irrigated and rainfed conditions, with corresponding genetic advances of 4.15 g and 2.82 g, respectively. In the combined analysis across environments, *h*² reached 0.58 with a genetic advance of 2.65 g. These moderate heritability values align with Gerema (2020) and suggest that substantial genetic progress can be achieved through selection for this trait.

Correlation analysis showed that 1000-grain weight was significantly positively associated with days to heading under irrigated conditions at both genotypic (r_g = 0.587**) and phenotypic (r_p = 0.485**) levels (Tables 17 & 18, Fig. 3 & 4). This relationship, also observed by Farshadfar *et al.,* (2012), suggests that phenological timing plays a critical role in determining grain weight by influencing the duration of the grain-filling period.

Biological yield

Analysis of variance indicated highly significant differences ($P \leq 0.01$) for environments and a significant ($P \leq 0.05$) genotype × environment (G × E) interaction for biological yield (Table 1). Although genotypic differences were non-significant, the significant G × E interaction suggests that biomass production was inconsistently expressed across moisture regimes, a finding consistent with Khan et al. (2007). Biological yield ranged from 7611–10296 kg ha^{-1} under irrigated conditions and 6667–9037 kg ha^{-1} under rainfed stress (Table 13). Moisture deficit resulted in a mean reduction of 1470 kg ha^{-1} (8789 vs. 7320 kg ha^{-1}), highlighting the substantial impact of drought on total biomass accumulation. Genotype G-7 produced the maximum biological yield under irrigation (10296 kg ha^{-1}), while G-17 excelled under rainfed conditions (9037 kg ha^{-1}).

Selection for stress resilience identified G-13 and G-17 as superior genotypes. G-13 demonstrated the highest stability across environments, exhibiting the lowest TOL (111.1), highest YSI (0.99), and lowest SSI (0.09). G-17 achieved the highest mean productivity (9111 kg ha^{-1}) and stress tolerance index (STI = 1.07), suggesting its ability to maintain high biomass potential under varying moisture levels (Table 13). According to Clarke *et al.,* (1984), SSI is a critical parameter for identifying genotypes that maintain performance under adverse conditions.

Genetic analysis revealed that environmental variances outweighed genetic effects in both environments (Table 16, Fig. 2). Broad-sense heritability (h^2) was low, estimated at 0.19 under irrigation and 0.20 under rainfed conditions, with corresponding genetic advances of 263.7 and 259.0 kg ha^{-1}. Across environments, h^2 dropped to 0.12, reflecting a strong environmental influence on this trait, as also reported by Kumar *et al.,* (2019). These low values suggest that selection for biological yield per se may be challenging in this population.

Correlation analysis showed that biological yield was genotypically associated with several yield-contributing traits. Under irrigated conditions, it correlated positively with grains $spike^{-1}$ ($r_g = 0.438^{**}$) and spikelets $spike^{-1}$ ($r_g = 0.756^{**}$) (Table 17, Fig. 3). Under rainfed stress, biological yield exhibited a significant positive genotypic correlation with grain weight $spike^{-1}$ ($r_g = 0.664^{**}$) but negative associations with days to heading ($r_g = -0.390^{*}$), plant height ($r_g = -0.580^{**}$), and grain yield ($r_g = -0.527^{**}$). Phenotypically, positive correlations were observed with spikelets $spike^{-1}$ ($r_p = 0.501^{**}$) under irrigation and grain weight per spike ($r_p = 0.349^{**}$) under rainfed stress, while significant negative correlations were noted with spikes m^{-2} ($r_p = -0.401^{*}$) and days to heading ($r_p = -0.390^{*}$) (Table 18, Fig. 4). These relationships, consistent with Abd-Allah *et al.,* (2018), suggest that while biomass is linked to spike development, its expression under drought may involve complex trade-offs with phenology and height.

Grain Yield

Analysis of variance revealed highly significant ($P \leq 0.01$) differences across environments and genotypes for grain yield, whereas the genotype × environment (G × E) interaction was non-significant (Table 1). This indicates that while productivity was significantly altered by moisture regimes, genotype rankings were relatively consistent, aligning with observations by Ilyas *et al.,* (2013). Yield ranged from 2389–4748 kg ha^{-1} under irrigation to 1711–3489 kg ha^{-1} under rainfed stress (Table 14). Genotype G-4 produced the maximum yield under irrigation (4748 kg ha^{-1}), while G-10 was most productive under rainfed conditions (3489 kg ha^{-1}).

Evaluation of stress tolerance indices identified G-22, G-4, and G-10 as superior performers, with G-22 achieving the highest Stress Tolerance Index (STI = 1.12) and Mean Productivity (MP = 3954 kg ha^{-1}) (Table 14). Stability analysis highlighted G-30 and G-7 as the least susceptible genotypes, exhibiting the lowest TOL (110.4–370.4) and SSI (0.14–0.34) values. As proposed by Nouri *et al.,* (2011), low TOL and SSI are critical for selecting resilient genotypes that maintain productivity under moisture deficit.

Genetic analysis showed that environmental variances exceeded genetic variances in both environments (Table 16, Fig. 2). Broad-sense heritability (h^2) was moderate under irrigation (0.48) and low under rainfed conditions (0.28), with corresponding genetic advances of 512.6 and 304.1 kg ha^{-1}. However, the combined analysis yielded a higher heritability (0.71) and genetic advance (523 kg ha^{-1}), primarily due to the low G × E variance relative to the total environmental variance. This pattern of heritability across moisture regimes aligns with findings by Khan *et al.,* (2007).

Genotypic correlation analysis revealed that grain yield was significantly positively associated with plant height ($r_g = 0.471^{**}$–0.687^{**}) and harvest index ($r_g = 0.928^{**}$–0.972^{*}) across environments (Table 17, Fig. 3). Conversely, yield exhibited significant negative correlations—both genotypically and phenotypically, with days to maturity ($r_g = -0.789^{**}$; $r_p = -0.652^{**}$), spikes m^{-2} ($r_g = -0.631^{**}$; $r_p = -0.359^{**}$), and grains per spike ($r_g = -0.372^{*}$; $r_p = -0.351^{*}$) under irrigated conditions (Table 18, Fig. 4). These associations, consistent with Khan *et al.,* (2011), suggest that yield in this germplasm is primarily influenced by biomass partitioning (harvest index) and stature, while late maturity and excessive tiller density may be detrimental under the tested environments.

Harvest index

Analysis of variance revealed highly significant differences ($P \leq 0.01$) among environments, genotypes, and their interactions (G × E) for harvest index (HI) (Table 1). The significant G × E interaction suggests inconsistent genotype performance across moisture regimes, corroborating the findings of Afridi and Khalil (2007). HI values ranged from 28–53% under irrigated conditions and 24–54% under rainfed stress (Table 15). Moisture deficit induced a 7% reduction in the mean HI (42% vs. 35%), indicating a significant disruption in dry matter partitioning to the grains under stress. Genotype G-22 recorded the highest HI under irrigation (53%), while G-10 was superior under rainfed conditions (54%).

Evaluation of stress tolerance indices identified G-22 and G-10 as superior performers, with G-22 attaining the highest stress tolerance index (STI = 1.34) and mean productivity (MP = 49). Stability analysis highlighted G-10 and G-7 as the least susceptible genotypes, exhibiting the lowest TOL (-9.40 and -7.58, respectively) and SSI (-1.17 and -1.25). Furthermore, G-7 and G-10 expressed the highest yield stability index (YSI = 1.23 and 1.21). As suggested by Mohammadijoo *et al.,* (2015), MP is a robust indicator for identifying genotypes that maintain high HI under both optimal and stressed conditions.

Genetic analysis indicated that environmental variances exceeded genetic variances in both environments (Table 16, Fig. 2). Broad-sense heritability (h^2) was moderate at 0.38 in both settings, with expected genetic advances of 5.05% (irrigated) and 6.18% (rainfed). However, across environments, h^2 increased to 0.61 with a genetic advance of 5.85%, aligning with the moderate heritability reported by Mohsin *et al.,* (2009).

Correlation analysis showed that HI was strongly linked to grain yield at the genotypic level across environments (r_g = 0.928** to 0.972**). Under irrigated conditions, HI correlated positively with plant height (r_g = 0.447**) and flag leaf area (r_g = 0.375*), but negatively with days to maturity (r_g = -0.770**) and grains spike^{-1} (r_g = -0.573**). Under rainfed stress, HI maintained a positive genotypic association with plant height (r_g = 0.779**) and days to heading (r_g = 0.352*), while showing a significant negative correlation with biological yield (r_g = -0.706**) (Table 17, Fig. 3). Phenotypically, HI exhibited a strong positive correlation with grain yield (r_p = 0.886** to 0.941**) and a significant negative association with maturity (r_p = -0.594**) (Table 18, Fig. 4), consistent with Chegdali *et al.,* (2022). These relationships suggest that early maturity and efficient biomass partitioning are critical for maintaining high HI under moisture-limited conditions

Table 1: Mean squares for days to heading, flag leaf area, days to maturity, plant height, spike m^{-2}, spike length, spikelets spike^{-1}, grains spike^{-1}, grain weight spike^{-1}, 1000- grain weight, biological yield, grain yield and harvest index of 30 wheat genotypes across two environments (irrigated and rainfed) at the University of Agriculture, Peshawar during 2022-23

SOV	Env	Rep w/n (Env)	Genotypes	G × E	Error	CV (%)
Df	(1)	(4)	(29)	(29)	(116)	-
Days to 50% headings	460.80**	6.89	9.30*	4.4.69**	1.62	1.07
Flag leaf area	828.38**	8.18	8.56**	3.37**	1.40	5.94
Days to maturity	408.01**	1.36	3.55*	1.83**	0.53	0.47
Plant height	3227.24**	9.97	26.24*	14.13**	3.59	2.34
Spikes meter^{-2}	474917**	5700	4390.3^{NS}	3488.5**	1702.2	9.60
Spike length	72.28**	0.97	2.96*	1.58**	0.52	6.37
Spikelets spike^{-1}	487.08**	8.12	2.69*	1.25**	0.36	2.74
Grains spike^{-1}	296.88^{NS}	49.40	23.04^{NS}	24.08**	10.97	4.55
Grain weight spike^{-1}	10.04 ^{NS}	3.17	0.1 8^{NS}	0.11^{NS}	0.08	13.13
1000-grain weight	1592.2**	34.6	41.0*	17.3**	6.43	6.11
Biological yield	97108495**	2640441	879286^{NS}	775985*	482124	8.62
Grain yield	64530993**	643699	1048075**	300805^{NS}	243529	15.88
Harvest index	2662.0*	145.71	180.61**	70.89*	44.25	17.23

*, **: significant at 5 and 1%, probability level, respectively, NS = non-Significant

Table 2: Means and stress indices for days to heading of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	116	115	115	1.33	0.99	0.43	0.91
G-2	118	117	117	1.00	0.99	0.32	0.95
G-3	120	116	118	4.00	0.97	1.24	0.95
G-4	121	117	119	3.67	0.97	1.13	0.97
G-5	121	117	119	4.00	0.97	1.23	0.98
G-6	122	118	120	4.00	0.97	1.22	0.99
G-7	121	119	120	2.67	0.98	0.82	0.99

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-8	121	117	119	4.33	0.96	1.33	0.97
G-9	123	117	120	6.33	0.95	1.92	0.98
G-10	122	118	120	4.33	0.96	1.32	0.99
G-11	121	117	119	4.33	0.96	1.33	0.97
G-12	121	117	119	4.33	0.96	1.33	0.97
G-13	121	120	120	0.33	1.00	0.10	1.00
G-14	121	120	120	1.33	0.99	0.41	0.99
G-15	121	117	119	4.00	0.97	1.23	0.97
G-16	121	120	120	1.33	0.99	0.41	0.99
G-17	123	117	120	6.00	0.95	1.82	0.99
G-18	123	117	120	6.00	0.95	1.82	0.98
G-19	122	119	120	2.67	0.98	0.82	0.99
G-20	121	118	119	3.67	0.97	1.13	0.98
G-21	121	115	118	5.67	0.95	1.74	0.96
G-22	119	117	118	2.33	0.98	0.73	0.96
G-23	121	119	120	2.33	0.98	0.72	0.99
G-24	119	118	119	0.67	0.99	0.21	0.97
G-25	120	117	118	3.00	0.98	0.93	0.96
G-26	120	116	118	3.67	0.97	1.14	0.96
G-27	121	121	121	0.00	1.00	0.00	1.01
G-28	121	118	119	3.67	0.97	1.13	0.98
G-29	120	116	118	4.00	0.97	1.24	0.96
G-30	120	118	119	2.33	0.98	0.72	0.97
Envir mean	121	118	119	3.24	0.97	1.00	0.97
LSD $_{(0.05)}$ for G under separate env	1.2	1.2					
LSD $_{(0.05)}$ for Env			0.1				
LSD $_{(0.05)}$ for Gen			1.0				
LSD $_{(0.05)}$ for G × E			1.2				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 3: Means and stress indices for flag leaf area (cm^2) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23.

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	21	16	19	5.37	0.75	1.28	0.72
G-2	21	16	18	5.04	0.76	1.23	0.69
G-3	21	16	18	4.99	0.76	1.23	0.68
G-4	24	20	22	4.67	0.81	0.99	0.98
G-5	23	19	21	3.83	0.83	0.86	0.91
G-6	23	19	21	4.35	0.81	0.97	0.89
G-7	20	16	18	3.69	0.82	0.94	0.69
G-8	21	19	20	1.47	0.93	0.36	0.84
G-9	23	18	21	5.44	0.77	1.19	0.88
G-10	22	18	20	3.92	0.82	0.90	0.85
G-11	21	19	20	2.12	0.90	0.52	0.81
G-12	21	15	18	5.84	0.72	1.43	0.66
G-13	22	21	22	0.96	0.96	0.22	0.96
G-14	22	14	18	8.21	0.63	1.91	0.63
G-15	24	17	20	6.65	0.72	1.43	0.85
G-16	22	18	20	4.28	0.81	0.98	0.84
G-17	23	19	21	4.40	0.81	0.98	0.88
G-18	23	18	20	4.71	0.79	1.06	0.85
G-19	21	19	20	2.12	0.90	0.53	0.79
G-20	22	19	20	3.68	0.83	0.85	0.85
G-21	23	18	21	4.90	0.79	1.09	0.85
G-22	24	19	21	4.77	0.80	1.03	0.94

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-23	19	15	17	4.25	0.78	1.12	0.61
G-24	23	19	21	4.59	0.80	1.01	0.89
G-25	21	16	19	4.17	0.80	1.04	0.70
G-26	22	18	20	4.46	0.80	1.03	0.81
G-27	21	16	19	5.05	0.76	1.22	0.71
G-28	23	17	20	5.47	0.76	1.23	0.82
G-29	21	19	20	2.21	0.90	0.54	0.81
G-30	22	18	20	3.11	0.86	0.73	0.84
Envir mean	22	18	20	4.29	0.81	1.00	0.81
LSD $_{(0.05)}$ for G under separate Env	0.9	1.3					
LSD $_{(0.05)}$ for Env			0.1				
LSD $_{(0.05)}$ for Gen			0.9				
LSD $_{(0.05)}$ for G × E			1.1				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 4: Means and stress indices for days to maturity of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	155	153	154	2.33	0.98	0.78	0.97
G-2	155	153	154	2.67	0.98	0.89	0.97
G-3	156	153	154	3.00	0.98	1.00	0.97
G-4	155	152	154	3.33	0.98	1.12	0.96
G-5	156	153	154	3.33	0.98	1.11	0.97
G-6	157	154	155	2.67	0.98	0.88	0.98
G-7	156	152	154	4.00	0.97	1.33	0.97
G-8	156	153	155	3.00	0.98	1.00	0.98
G-9	156	152	154	4.00	0.97	1.33	0.97
G-10	156	154	155	2.00	0.99	0.67	0.98
G-11	156	155	155	1.33	0.99	0.44	0.98
G-12	156	153	155	3.00	0.98	1.00	0.98
G-13	156	152	154	4.00	0.97	1.33	0.97
G-14	157	153	155	4.00	0.97	1.33	0.98
G-15	157	152	154	5.00	0.97	1.65	0.97
G-16	155	153	154	1.67	0.99	0.56	0.97
G-17	157	153	155	4.00	0.97	1.32	0.98
G-18	156	153	155	3.00	0.98	1.00	0.98
G-19	157	154	155	3.00	0.98	1.00	0.98
G-20	156	153	155	2.67	0.98	0.89	0.98
G-21	156	154	155	1.67	0.99	0.56	0.98
G-22	156	155	155	1.67	0.99	0.55	0.99
G-23	156	154	155	2.00	0.99	0.66	0.98
G-24	157	154	155	3.00	0.98	0.99	0.99
G-25	157	154	155	3.00	0.98	0.99	0.99
G-26	159	154	157	4.67	0.97	1.53	1.00
G-27	157	155	156	1.67	0.99	0.55	0.99
G-28	157	156	156	1.00	0.99	0.33	1.00
G-29	158	154	156	4.67	0.97	1.53	0.99
G-30	159	154	156	5.00	0.97	1.63	1.00
Envir mean	156	153	155	3.01	0.98	1.00	0.98
LSD $_{(0.05)}$ for G under separate env				0.7	0.6		
LSD $_{(0.05)}$ for Env						0.1	
LSD$_{(0.05)}$ for Gen						0.7	
LSD$_{(0.05)}$ for G × E						0.7	

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index

Table 5: Means and stress indices for plant height (cm) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	81.0	77.0	79.5	4.97	0.94	0.61	0.87
G-2	89.2	76.3	82.8	12.87	0.86	1.45	0.94
G-3	85.9	76.0	81.0	9.90	0.88	1.16	0.90
G-4	90.3	77.0	83.6	13.30	0.85	1.48	0.96
G-5	88.6	75.3	82.0	13.27	0.85	1.50	0.92
G-6	84.4	75.7	80.0	8.70	0.90	1.04	0.88
G-7	86.0	77.3	81.7	8.65	0.90	1.01	0.92
G-8	82.9	77.3	80.1	5.60	0.93	0.68	0.89
G-9	81.8	76.0	78.9	5.81	0.93	0.71	0.86
G-10	90.3	83.7	87.0	6.67	0.93	0.74	1.04
G-11	90.1	81.3	85.7	8.76	0.90	0.98	1.01
G-12	84.3	77.0	80.7	7.33	0.91	0.87	0.90
G-13	82.3	76.3	79.3	5.93	0.93	0.72	0.87
G-14	78.3	77.0	77.7	1.33	0.98	0.17	0.83
G-15	79.3	76.7	78.0	2.67	0.97	0.34	0.84
G-16	83.4	77.0	80.2	6.39	0.92	0.77	0.89
G-17	83.6	75.0	79.3	8.60	0.90	1.03	0.87
G-18	82.3	75.0	78.6	7.27	0.91	0.89	0.85
G-19	85.9	77.0	81.5	8.93	0.90	1.04	0.91
G-20	87.9	75.0	81.4	12.87	0.85	1.47	0.91
G-21	83.1	76.0	79.5	7.07	0.91	0.85	0.87
G-22	90.1	76.3	83.2	13.73	0.85	1.53	0.95
G-23	86.8	76.0	81.4	10.80	0.88	1.25	0.91
G-24	83.3	75.3	79.3	7.97	0.90	0.96	0.87
G-25	83.5	76.3	79.9	7.13	0.91	0.86	0.88
G-26	83.6	76.7	80.1	6.93	0.92	0.83	0.89
G-27	86.9	77.0	82.0	9.93	0.89	1.15	0.92
G-28	87.1	75.7	81.4	11.43	0.87	1.32	0.91
G-29	86.0	75.0	80.5	10.98	0.87	1.28	0.89
G-30	83.3	75.0	79.1	8.27	0.90	1.00	0.86
Envir mean	85.1	76.6	80.8	8.47	0.90	0.99	0.90
LSD $_{(0.05)}$ for G under separate env	2.3	1.0					
LSD $_{(0.05)}$ for Env			0.1				
LSD $_{(0.05)}$ for Gen			1.8				
LSD $_{(0.05)}$ for G × E			1.8				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 6: Means and stress indices for spikes m^{-2} of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	541	388	464	153	0.72	1.33	0.91
G-2	440	355	398	85.0	0.81	0.90	0.68
G-3	444	324	354	120.0	0.73	1.27	0.62
G-4	469	385	385	84.4	0.82	0.84	0.78
G-5	410	369	390	40.3	0.90	0.46	0.65
G-6	493	398	446	95.0	0.81	0.90	0.85
G-7	460	377	418	82.7	0.82	0.84	0.75
G-8	473	374	423	97.3	0.79	0.97	0.76
G-9	378	391	385	-13.5	1.04	-0.17	0.64
G-10	465	389	427	75.4	0.84	0.76	0.78
G-11	502	378	440	124	0.75	1.16	0.82

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-12	450	340	395	109	0.76	1.14	0.66
G-13	514	411	463	103	0.80	0.94	0.91
G-14	483	408	445	74	0.85	0.72	0.85
G-15	521	390	455	130	0.75	1.17	0.88
G-16	459	332	396	126	0.72	1.29	0.66
G-17	475	337	406	138	0.71	1.36	0.69
G-18	555	380	468	176	0.68	1.48	0.91
G-19	496	345	420	151	0.70	1.42	0.74
G-20	474	407	440	67.4	0.86	0.67	0.83
G-21	570	412	491	158	0.72	1.30	1.01
G-22	463	434	449	29.0	0.94	0.29	0.87
G-23	438	395	417	43.1	0.90	0.46	0.75
G-24	472	445	458	27.5	0.94	0.27	0.91
G-25	504	387	445	117	0.77	1.09	0.84
G-26	544	337	441	207	0.62	1.78	0.79
G-27	488	368	428	119	0.76	1.14	0.78
G-28	469	366	418	103	0.78	1.03	0.74
G-29	523	362	443	161	0.69	1.44	0.82
G-30	459	363	411	96.0	0.79	0.98	0.72
Envir Mean	481	378	430	103	0.79	0.98	0.79
LSD $_{(0.05)}$ for G under separate Env	42.5	34.9					
LSD $_{(0.05)}$ Env			3.3				
LSD $_{(0.05)}$ Gen			28.5				
LSD $_{(0.05)}$ for GxE			38.5				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 7: Means and stress indices for spikes length (cm) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23.

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	11.7	10.2	10.9	1.44	0.88	1.17	0.83
G-2	11.8	10.6	11.2	1.18	0.90	0.95	0.87
G-3	11.8	10.6	11.2	1.18	0.90	0.95	0.87
G-4	11.1	10.4	10.8	0.68	0.94	0.58	0.80
G-5	11.6	10.8	11.2	0.80	0.93	0.66	0.86
G-6	10.0	10.1	10.1	-0.16	1.02	-0.15	0.70
G-7	11.4	10.5	10.9	0.91	0.92	0.75	0.83
G-8	13.5	10.5	12.0	3.03	0.78	2.13	0.98
G-9	12.3	10.0	11.2	2.28	0.81	1.75	0.86
G-10	12.2	12.3	12.2	-0.02	1.00	-0.01	1.04
G-11	10.5	10.7	10.6	-0.23	1.02	-0.21	0.78
G-12	12.0	10.8	11.4	1.15	0.90	0.91	0.90
G-13	12.0	11.7	11.9	0.39	0.97	0.31	0.97
G-14	12.8	12.3	12.5	0.46	0.96	0.34	1.09
G-15	14.0	10.7	12.3	3.34	0.76	2.26	1.04
G-16	10.7	9.9	10.3	0.74	0.93	0.65	0.74
G-17	11.7	10.5	11.1	1.23	0.90	0.99	0.85
G-18	10.3	9.9	10.1	0.38	0.96	0.35	0.70
G-19	11.7	9.6	10.7	2.09	0.82	1.69	0.78
G-20	12.8	11.3	12.0	1.48	0.88	1.10	1.00
G-21	11.2	11.1	11.2	0.08	0.99	0.07	0.87
G-22	14.0	11.2	12.6	2.78	0.80	1.88	1.09
G-23	14.0	10.9	12.5	3.12	0.78	2.11	1.06
G-24	12.6	11.1	11.9	1.44	0.89	1.08	0.97
G-25	12.8	9.61	11.2	3.17	0.75	2.35	0.85
G-26	12.0	10.4	11.2	1.61	0.87	1.27	0.87

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-27	11.8	11.6	11.7	0.19	0.98	0.15	0.96
G-28	11.5	10.6	11.1	0.94	0.92	0.77	0.85
G-29	12.4	11.1	11.7	1.34	0.89	1.02	0.95
G-30	12.0	11.0	11.5	1.00	0.92	0.79	0.92
Envir mean	12.0	10.7	11.4	1.27	0.90	0.96	0.90
LSD $_{(0.05)}$ for G under separate Env	0.8	0.5					
LSD $_{(0.05)}$ for Env			0.04				
LSD $_{(0.05)}$ for Gen			0.61				
LSD$_{(0.05)}$ for GxE			0.68				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 8. Variance components, heritability (h^2), and expected genetic advance (GA) for days to heading, flag leaf area, days to maturity, plant height, spikes m^{-2} and spike length of 30 wheat genotypes under each environment and across at the University of Agriculture, Peshawar during 2022-23

Trait	Environment	Vg	Vge	Ve	h^2	GA
Heading (days)	Irrigated	1.95	-	1.71	0.53	1.79
	Rainfed	1.63	-	1.53	0.52	1.61
	Across Envir	0.77	1.02	1.62	0.50	1.08
Flag leaf area (cm^2)	Irrigated	1.12	-	1.78	0.53	1.35
	Rainfed	1.92	-	1.78	0.52	1.75
	Across Envir	0.86	0.66	1.40	0.61	1.27
Maturity (days)	Irrigated	0.72	-	0.62	0.54	1.09
	Rainfed	0.73	-	0.44	0.62	1.18
	Across Envir	0.29	0.44	0.53	0.48	0.65
Plant height (cm)	Irrigated	8.20	-	6.04	0.58	3.81
	Rainfed	2.86	-	1.14	0.72	2.51
	Across Envir	2.02	3.51	3.59	0.46	1.69
Spike m^{-2} (no)	Irrigated	1082	-	2033	0.35	34.0
	Rainfed	409.3	-	1371	0.23	17.0
	Across Envir	150.3	595.5	1702	0.21	9.75
Spike length (cm)	Irrigated	0.81	-	0.75	0.52	1.14
	Rainfed	0.35	-	0.30	0.53	0.76
	Across Envir	0.23	0.35	0.52	0.47	0.57

Vg = Genetic variance, Vge = Genetic × Environment variance, Ve = Environmental variance, h^2 = heritability, GA = Expected genetic advance

Table 9: Means and stress indices for spikelets $spike^{-1}$ of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	23	21	22	2.0	0.91	0.62	0.87
G-2	23	21	22	2.0	0.91	0.62	0.87
G-3	23	21	22	2.0	0.91	0.61	0.90
G-4	24	22	23	2.0	0.92	0.59	0.96
G-5	25	23	24	2.0	0.92	0.57	1.02
G-6	23	21	22	1.9	0.92	0.60	0.86
G-7	23	23	24	2.0	0.92	0.58	0.99
G-8	24	22	23	2.0	0.92	0.59	0.96
G-9	24	21	22	3.0	0.87	0.91	0.88
G-10	24	20	22	4.0	0.83	1.21	0.85
G-11	23.	20	21	3.5	0.85	1.08	0.81
G-12	23	20	22	3.6	0.85	1.11	0.83
G-13	23	20	22	2.8	0.88	0.87	0.85
G-14	23	19	21	3.4	0.85	1.08	0.78
G-15	24	20	22	4.1	0.82	1.25	0.83
G-16	24	20	22	3.8	0.84	1.15	0.84
G-17	23	19	21	3.9	0.83	1.19	0.81

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-18	24	20	22	4.1	0.83	1.23	0.84
G-19	24	19	21	4.5	0.81	1.35	0.82
G-20	24	20.	22	3.5	0.85	1.06	0.85
G-21	24	20	22	3.90	0.84	1.17	0.85
G-22	23	20	21	3.5	0.85	1.08	0.81
G-23	24	19	21	4.9	0.80	1.46	0.81
G-24	24	20	22	4.6	0.81	1.36	0.85
G-25	24	20	22	3.9	0.84	1.17	0.85
G-26	24	20	22	3.7	0.84	1.11	0.84
G-27	24	20	22	3.4	0.85	1.04	0.85
G-28	23	20	21	3.8	0.84	1.16	0.82
G-29	23	21	22	2.9	0.87	0.90	0.87
G-30	24	19	22	4.3	0.82	1.29	0.82
Envir mean	24	20	22	3.29	0.86	1.00	0.86
LSD $_{(0.05)}$ for Env	0.4	0.7					
LSD $_{(0.05)}$ for Env			0.1				
LSD $_{(0.05)}$ for Gen			0.5				
LSD $_{(0.05)}$ for G × E			0.6				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

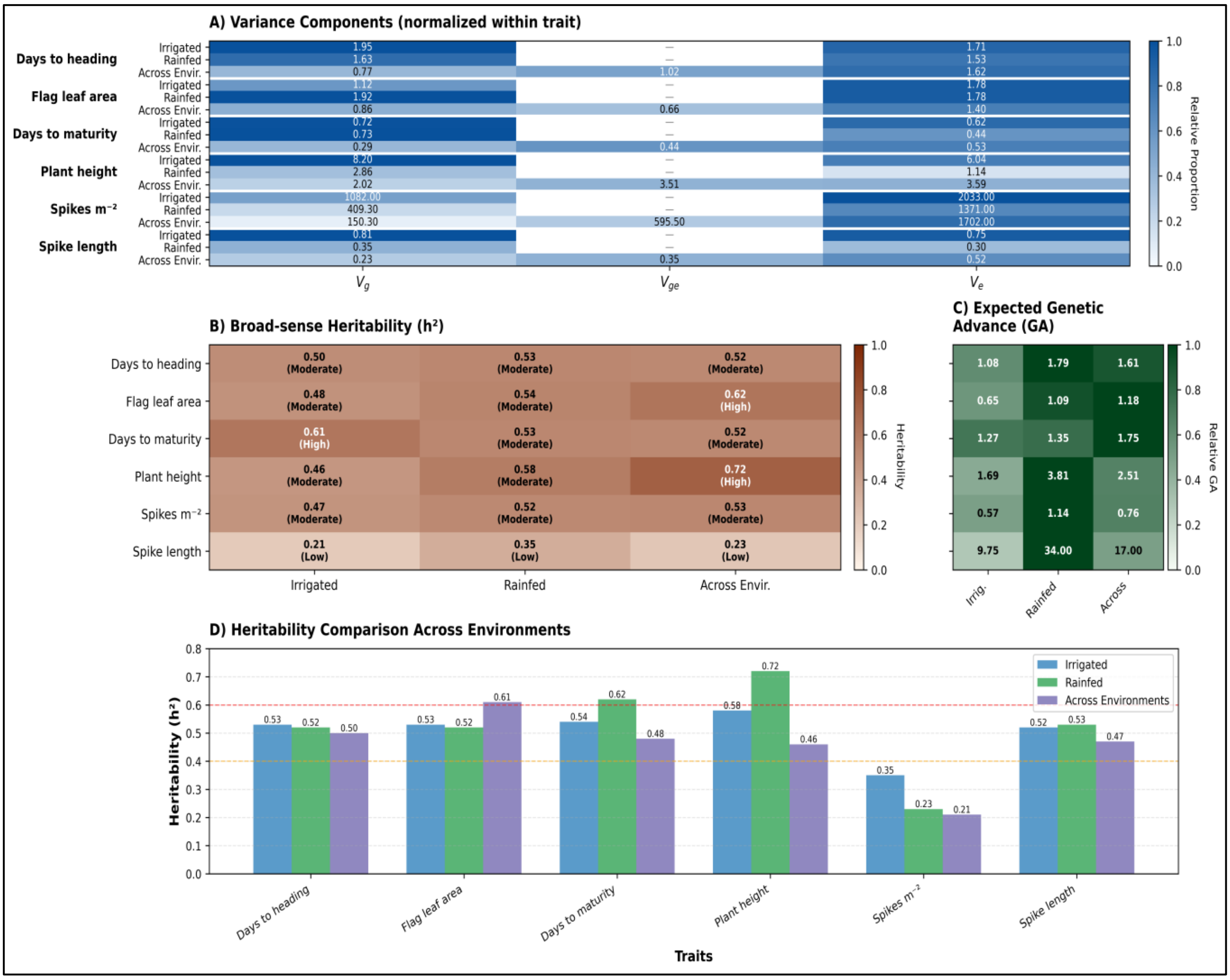

Figure 1: Integrated analysis of genetic parameters for six wheat traits across three environments. (A) Normalized variance components showing relative contributions of genetic (V_g), genotype × environment (V_{ge}), and environmental (V_e) variance. **(B)** Broad-sense heritability (h²) with categorical classifications (high ≥ 0.60, moderate 0.40–0.59, low <

0.40). **(C)** Expected genetic advance (GA) normalized within traits. **(D)** Cross-environment heritability comparison with threshold indicators. Data from 30 wheat genotypes evaluated at the University of Agriculture, Peshawar (2022-23).

Table 10: Means and stress indices for grains spike^{-1} of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	73	72	72	0.95	0.99	0.33	0.94
G-2	71	65	68	6.05	0.91	2.18	0.83
G-3	73	64	69	9.33	0.87	3.24	0.85
G-4	75	71	73	3.98	0.95	1.35	0.96
G-5	75	73	74	1.67	0.98	0.57	0.99
G-6	75	73	74	2.33	0.97	0.79	0.99
G-7	76	65	70	11.0	0.85	3.70	0.88
G-8	76	72	74	3.92	0.95	1.32	0.98
G-9	75	74	75	0.77	0.99	0.26	1.01
G-10	73	68	71	5.67	0.92	1.97	0.90
G-11	75	72	73	2.67	0.96	0.91	0.97
G-12	74	72	73	2.00	0.97	0.69	0.95
G-13	76	72	74	3.88	0.95	1.30	0.98
G-14	73	72	73	1.04	0.99	0.36	0.95
G-15	74	71	73	3.00	0.96	1.03	0.95
G-16	75	75	75	0.32	1.00	0.11	1.02
G-17	76	72	74	4.00	0.95	1.35	0.98
G-18	75	73	74	1.59	0.98	0.54	0.99
G-19	76	73	74	3.33	0.96	1.12	1.00
G-20	74	72	73	2.25	0.97	0.77	0.97
G-21	73	72	73	1.67	0.98	0.58	0.95
G-22	69	74	72	5.00	1.07	-1.84	0.93
G-23	71	71	71	0.00	1.00	0.00	0.91
G-24	77	76	76	1.09	0.99	0.36	1.05
G-25	78	70	74	7.92	0.90	2.59	0.91
G-26	76	70	73	6.44	0.92	2.14	1.05
G-27	70	77	74	7.00	1.10	-2.54	0.98
G-28	76	70	73	6.00	0.92	2.01	0.96
G-29	76	75	76	1.25	0.98	0.42	1.03
G-30	77	71	74	5.61	0.93	1.88	0.98
Envir mean	74	72	73	2.92	0.96	0.98	0.96
LSD $_{(0.05)}$ for G under separate env	2.1	3.8					
LSD $_{(0.05)}$ for Env			0.31				
LSD $_{(0.05)}$ for Gen			2.37				
LSD $_{(0.05)}$ for G × E			3.09				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 11: Means and stress indices for grain weight spike^{-1} (g) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	2.5	2.2	2.4	0.26	0.90	0.53	0.97
G-2	2.5	2.2	2.4	0.29	0.89	0.58	0.96
G-3	2.1	1.1	1.6	0.98	0.54	2.36	0.41
G-4	2.5	2.2	2.3	0.30	0.88	0.61	0.93
G-5	2.2	2.3	2.2	-0.12	1.05	-0.27	0.85
G-6	2.1	1.9	2.0	0.20	0.90	0.50	0.66
G-7	2.5	1.8	2.2	0.78	0.70	1.55	0.78
G-8	2.5	1.9	2.2	0.54	0.78	1.17	0.82
G-9	2.4	1.8	2.1	0.58	0.76	1.11	0.76
G-10	2.4	2.0	2.2	0.41	0.83	1..22	0.86
G-11	2.5	2.0	2.2	0.56	0.78	1.13	0.85

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-12	2.2	1.7	2.0	0.52	0.77	1.17	0.67
G-13	2.0	1.8	1.9	0.28	0.86	0.70	0.63
G-14	2.6	2.0	2.3	0.57	0.78	1.12	0.90
G-15	2.5	1.7	2.1	0.76	0.69	1.57	0.72
G-16	2.3	2.0	2.2	0.35	0.85	0.76	0.81
G-17	2.2	2.0	2.1	0.27	0.88	0.61	0.77
G-18	2.5	2.1	2.3	0.31	0.87	0.65	0.91
G-19	2.4	2.1	2.3	0.26	0.89	0.55	0.89
G-20	2.5	2.0	2.2	0.53	0.79	1.08	0.85
G-21	2.5	1.7	2.1	0.80	0.68	1.60	0.76
G-22	2.4	2.1	2.3	0.30	0.88	0.63	0.88
G-23	2.5	2.4	2.4	0.13	0.95	0.26	1.02
G-24	2.5	1.9	2.2	0.59	0.77	1.19	0.85
G-25	2.4	1.7	2.0	0.66	0.72	1.42	0.70
G-26	2.1	1.8	2.0	0.26	0.88	0.63	0.67
G-27	2.6	1.4	2.0	1.14	0.56	2.25	0.65
G-28	2.8	2.0	2.4	0.77	0.72	1.42	0.95
G-29	2.3	1.8	2.1	0.54	0.77	1.18	0.72
G-30	2.6	2.2	2.4	0.37	0.86	0.73	0.99
Envir mean	2.4	1.9	2.2	0.5	0.81	0.99	0.81
LSD $_{(0.05)}$ for G under separate Env	0.2	0.3					
LSD $_{(0.05)}$ for Env			0.08				
LSD $_{(0.05)}$ for Gen			0.16				
LSD $_{(0.05)}$ for G × E			0.27				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 12: Means and stress indices for 1000- grain weight (g) of 30 wheat genotypes in irrigated and rainfed environments at The University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	41.9	40.9	41.4	0.93	0.98	0.17	0.87
G-2	40.2	39.5	39.9	0.70	0.98	0.13	0.80
G-3	40.8	37.9	39.3	2.90	0.93	0.53	0.78
G-4	39.2	37.0	38.1	2.20	0.94	0.42	0.73
G-5	42.6	36.2	39.4	6.47	0.85	1.13	0.78
G-6	42.0	35.8	38.9	6.20	0.85	1.10	0.76
G-7	41.9	36.3	39.1	5.63	0.87	1.01	0.77
G-8	45.7	37.5	41.6	8.23	0.82	1.35	0.86
G-9	45.9	42.6	44.3	3.23	0.93	0.53	0.99
G-10	47.4	40.5	44.0	6.97	0.85	1.10	0.97
G-11	41.1	41.1	40.1	2.06	0.95	0.38	0.81
G-12	49.1	38.5	43.8	10.6	0.78	1.62	0.96
G-13	49.6	44.7	47.2	4.83	0.90	0.73	1.12
G-14	45.9	42.1	44.0	3.73	0.92	0.61	0.98
G-15	45.9	43.6	44.7	2.27	0.95	0.37	1.01
G-16	45.9	39.0	42.4	6.87	0.85	1.12	0.90
G-17	49.5	38.5	44.0	11.0	0.78	1.66	0.96
G-18	52.4	36.8	44.6	15.6	0.70	2.23	0.97
G-19	51.3	40.9	46.1	10.4	0.80	1.52	1.06
G-20	48.8	38.9	43.9	9.90	0.80	1.52	0.96
G-21	45.9	38.2	42.1	7.63	0.83	1.24	0.89
G-22	45.9	39.7	42.8	6.20	0.86	1.01	0.92
G-23	44.0	37.2	40.6	6.73	0.85	1.15	0.83
G-24	44.9	35.6	40.3	9.30	0.79	1.55	0.81
G-25	40.4	35.8	38.1	4.65	0.88	0.86	0.73
G-26	40.1	35.2	37.7	4.90	0.88	0.91	0.71

Genotypes	**IR**	**RF**	**MP**	**TOL**	**YSI**	**SSI**	**STI**
G-27	41.9	35.9	38.9	6.08	0.85	1.09	0.76
G-28	40.9	38.5	39.7	2.38	0.94	0.44	0.79
G-29	42.0	37.0	39.5	4.97	0.88	0.88	0.79
G-30	41.9	37.1	39.5	4.83	0.88	0.86	0.78
Envir mean	44	39	41.5	5.95	0.87	0.97	0.87
LSD $_{(0.05)}$ for G under separate Env	2.8	1.9					
LSD $_{(0.05)}$ for Env	0.26						
LSD $_{(0.05)}$ for Gen	2.00						
LSD $_{(0.05)}$ for G × E	2.37						

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index

Table 13: Means and stress indices for biological yield (kg ha^{-1}) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	**IR**	**RF**	**MP**	**TOL**	**YSI**	**SSI**	**STI**
G-1	8556	7789	8172	767	0.91	0.54	0.86
G-2	8889	7722	8306	1167	0.87	0.79	0.89
G-3	8667	7067	7868	1600	0.82	1.10	0.79
G-4	9111	7633	8372	1478	0.84	0.97	0.90
G-5	9185	6822	8004	2362	0.74	1.54	0.81
G-6	8789	6956	7872	1833	0.79	1.25	0.79
G-7	10296	7400	8848	2896	0.72	1.68	0.99
G-8	9444	7400	8422	2044	0.78	1.30	0.90
G-9	9222	7222	8222	2000	0.78	1.30	0.86
G-10	9185	6668	7926	2519	0.73	1.64	0.79
G-11	8333	6711	7522	1622	0.81	1.16	0.72
G-12	8889	7389	8139	1500	0.83	1.01	0.85
G-13	7611	7500	7556	111	0.99	0.09	0.74
G-14	8444	6944	7694	1500	0.82	1.06	0.76
G-15	8789	6956	7872	1833	0.79	1.25	0.79
G-16	9111	7556	8333	1556	0.83	1.02	0.89
G-17	9185	9037	9111	148	0.98	0.10	1.07
G-18	8777	6833	7806	1944	0.78	1.33	0.78
G-19	8222	7533	7878	688.8	0.92	0.50	0.80
G-20	8444	7567	8006	877.8	0.90	0.62	0.83
G-21	8222	7467	7844	755.6	0.91	0.55	0.79
G-22	8444	7522	7983	922.2	0.89	0.65	0.82
G-23	9667	7222	8444	2444	0.75	1.51	0.90
G-24	8667	6722	7694	1944	0.78	1.34	0.75
G-25	9056	6722	7889	2333	0.74	1.54	0.79
G-26	9011	7667	8339	1344	0.85	0.89	0.89
G-27	7667	6944	7306	722	0.91	0.56	0.69
G-28	8444	7167	7806	1278	0.85	0.91	0.78
G-29	8778	7178	7978	1600	0.82	1.09	0.82
G-30	8556	8278	8417	277.8	0.97	0.19	0.92
Envir mean	8789	7320	8054	1469	0.84	0.98	0.83
LSD $_{(0.05)}$ for G under separate Env	684	625					
LSD $_{(0.05)}$ for Env			70.9				
LSD $_{(0.05)}$ for Gen			424.7				
LSD $_{(0.05)}$ for G × E			648.3				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 14: Means and stress indices for grain yield (kg ha^{-1}) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	3056	1833	2444	1222	0.60	1.24	0.41
G-2	3656	2000	2828	1656	0.55	1.40	0.53
G-3	4352	2722	3537	1630	0.63	1.16	0.86
G-4	4748	3056	3902	1693	0.64	1.10	1.06
G-5	3982	2656	3319	1326	0.67	1.03	0.77
G-6	3637	3056	3346	581	0.84	0.49	0.81
G-7	3389	3019	3204	370	0.89	0.34	0.75
G-8	3519	2618	3068	900	0.74	0.79	0.67
G-9	4167	2833	3500	1333	0.68	0.99	0.86
G-10	4056	3489	3772	566	0.86	0.43	1.03
G-11	3822	2622	3222	2000	0.69	0.97	0.73
G-12	4389	2556	3472	1833	0.58	1.29	0.82
G-13	3389	2322	2856	1067	0.69	0.97	0.57
G-14	3704	2756	3230	948.	0.74	0.79	0.74
G-15	3759	2574	3167	1185	0.68	0.98	0.70
G-16	3722	2756	3239	967	0.74	0.80	0.75
G-17	3267	2607	2937	659	0.80	0.62	0.62
G-18	3444	2604	3024	841	0.76	0.76	0.65
G-19	3667	2152	2909	1515	0.59	1.28	0.57
G-20	3711	1933	2822	1778	0.52	1.48	0.52
G-21	3833	1889	2861	1944	0.49	1.57	0.53
G-22	4500	3407	3954	1093	0.76	0.75	1.12
G-23	4167	2778	3472	1389	0.67	1.03	0.84
G-24	3452	1963	2707	1489	0.57	1.33	0.49
G-25	3667	2015	2841	1652	0.55	1.39	0.54
G-26	3444	2211	2828	1233	0.64	1.11	0.55
G-27	3667	2156	2911	1511	0.59	1.28	0.58
G-28	3833	2667	3250	1167	0.70	0.94	0.74
G-29	2778	1711	2244	1067	0.62	1.19	0.35
G-30	2388	2279	2334	110	0.95	0.14	0.40
Envir mean	3705	2508	3107	1198	0.68	0.99	0.69
LSD $_{(0.05)}$ for G under separate Env	409	516					
LSD $_{(0.05)}$ for Env			35.0				
LSD $_{(0.05)}$ for Gen			264.4				
LSD $_{(0.05)}$ for G × E			460.8				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 15: Means and stress indices for harvest index (%) of 30 wheat genotypes in irrigated and rainfed environments at the University of Agriculture, Peshawar during 2022-23

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-1	36	24	30	11.9	0.67	1.84	0.47
G-2	41	26	37	15.1	0.63	2.02	0.60
G-3	50	38	44	12.0	0.76	1.32	1.06
G-4	52	40	46	12.3	0.76	1.30	1.16
G-5	43	39	41	4.8	0.89	0.61	0.93
G-6	42	44	43	-2.3	1.05	-0.30	1.01
G-7	33	41	37	-7.6	1.23	-1.25	0.76
G-8	37	36	36	1.8	0.95	0.27	0.74
G-9	45	39	42	6.0	0.87	0.73	0.98
G-10	44	54	49	-9.4	1.21	-1.17	1.31
G-11	46	39	42	6.7	0.85	0.81	1.00
G-12	49	35	42	14.7	0.70	1.64	0.95

Genotypes	IR	RF	MP	TOL	YSI	SSI	STI
G-13	45	31	38	13.5	0.70	1.47	0.77
G-14	44	40	42	4.1	0.91	0.52	0.97
G-15	43	37	40	5.9	0.86	0.75	0.90
G-16	41	37	39	4.4	0.89	0.59	0.83
G-17	36	29	32	6.8	0.81	1.05	0.57
G-18	40	39	39	0.8	0.98	0.11	0.84
G-19	45	29	37	16.0	0.65	1.95	0.73
G-20	44	26	35	18.1	0.59	2.26	0.64
G-21	47	26	36	20.7	0.56	2.45	0.67
G-22	53	45	49	8.14	0.85	0.84	1.34
G-23	44	39	41	5.2	0.88	0.66	0.94
G-24	40	30	35	10.3	0.74	1.42	0.66
G-25	41	30	35	10.4	0.74	1.42	0.68
G-26	39	28	33	10.3	0.73	1.48	0.60
G-27	48	39	44	8.6	0.82	0.98	1.05
G-28	45	33	39	12.8	0.72	1.56	0.82
G-29	32	26	29	5.3	0.83	0.92	0.46
G-30	28	25	27	3.2	0.89	0.63	0.39
Envir Mean	42	35	38.6	7.69	0.82	0.97	0.83
LSD $_{(0.05)}$ for G under separate Env	6.8	5.7					
LSD $_{(0.05)}$ for Env			0.5				
LSD $_{(0.05)}$ for Gen			4.1				
LSD $_{(0.05)}$ for G × E			6.2				

IR= Irrigated, RF= Rainfed, MP= Mean productivity, TOL= Tolerance index, YSI= yield Stability index, SSI= Stress Susceptibility index, STI= Stress Tolerance index.

Table 16: Variance components, heritability (h^2), and expected genetic advance (GA) for spikelets spike^{-1}, grains spike^{-1}, grain weight spike^{-1}, 1000-grain weight, biological yield (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index of 30 wheat genotypes under each environment and across at the University of Agriculture, Peshawar during 2022-23

Trait	Environment	Vg	Vge	Ve	h^2	GA
Spikelets spike^{-1} (no.)	Irrigated	0.18	-	0.14	0.56	0.56
	Rainfed	0.89	-	0.58	0.61	1.30
	Across Envir	0.24	0.30	0.36	0.53	0.63
Grains spike^{-1} (no.)	Irrigated	2.69	-	4.78	0.36	1.73
	Rainfed	4.04	-	15.98	0.20	1.58
	Across Envir	0.21	3.15	10.38	0.06	0.20
Grains weight spike^{-1} (no.)	Irrigated	0.03	-	0.10	0.26	0.16
	Rainfed	0.06	-	0.10	0.40	0.28
	Across Envir	0.01	0.01	0.08	0.42	0.13
1000- Grain weight (g)	Irrigated	10.36	-	8.82	0.54	4.15
	Rainfed	4.78	-	4.04	0.54	2.82
	Across Envir	3.95	3.62	6.43	0.58	2.65
Biological yield (kg ha^{-1})	Irrigated	120853	-	526021	0.19	263.7
	Rainfed	109489	-	438226	0.20	259.6
	Across Envir	17217	97954	482124	0.12	78.9
Grain yield (kg ha^{-1})	Irrigated	176355	-	188204	0.48	512.6
	Rainfed	110919	-	298854	0.27	304.1
	Across Envir	124545	19092	243529	0.71	523.0
Harvest index (%)	Irrigated	21.87	-	35.92	0.38	5.05
	Rainfed	32.5	-	52.6	0.38	6.18
	Across Envir	18.29	8.88	44.25	0.61	5.85

Vg = Genetic variance, Vge = Genetic × Environment variance, Ve = Environmental variance, h^2 = heritability, GA = Expected genetic advanc

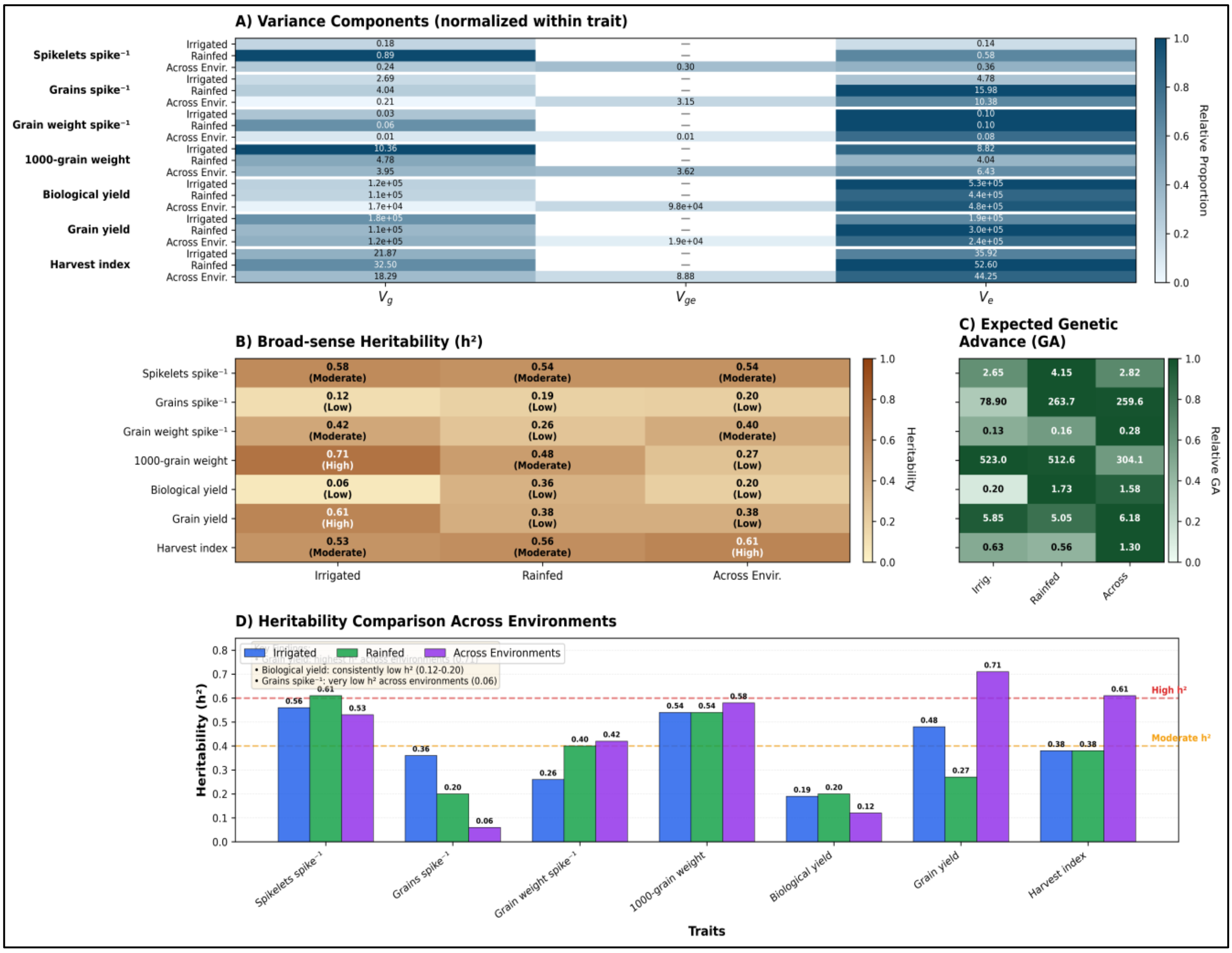

Figure 2: Integrated genetic parameter analysis for seven yield and yield component traits across three environments. **(A)** Normalized variance components showing relative contributions of genetic (V_g), genotype × environment (V_{ge}), and environmental (V_e) variance. **(B)** Broad-sense heritability (*h*²) with categorical classifications. **(C)** Expected genetic advance (GA) normalized within traits. **(D)** Cross-environment heritability comparison with threshold indicators and key findings highlighted. Data from 30 wheat genotypes evaluated at the University of Agriculture, Peshawar (2022-23). Grain yield showed exceptional heritability across environments (0.71), while biological yield and grains spike⁻¹ exhibited low heritability, indicating strong environmental influence.

Table 17: Genotypic correlations for various yield and yield related traits of 32 wheat genotypes under irrigated (above diagonal) and rainfed (below diagonal) condition evaluated at the University of Agriculture, Peshawar during 2022-2023

Traits	DH	DM	FLA	PH	SPM	SL	SPS	GPS	GWS	TGW	BY	GY	HI
DH	-	0.175	0.150	0.046	-0.408*	-0.274	0.284	0.093	-0.241	0.587**	0.336	0.214	0.115
DM	0.110	-	-0.025	-0.352*	0.403*	0.293	-0.066	0.451**	0.062	-0.149	-0.120	-0.789**	-0.770**
FLA	-0.103	0.064	-	-0.108	0.004	-0.083	-0.049	0.305	0.315	0.217	-0.310	0.288	0.375*
PH	0.129	0.038	-0.025	-	-0.406*	-0.152	0.289	-0.458**	-0.101	-0.317	0.111	0.471*	0.447**
SPM	0.065	0.074	0.336	0.003	-	-0.265	-0.372*	0.215	0.110	0.130	-0.805**	-0.631**	-0.330
SL	0.300	0.175	-0.069	0.310	0.672**	-	0.075	-0.160	0.490**	0.049	0.025	0.188	0.192
SPS	-0.244	-0.533**	0.194	-0.033	-0.051	-0.180	-	0.061	0.114	-0.105	0.756**	0.196	-0.057
GPS	0.261	0.502**	0.424*	-0.403*	0.822**	0.057	-0.486**	-	0.189	-0.019	0.438**	-0.372*	-0.573**
GWS	-0.226	0.154	0.287	-0.198	0.630**	-0.052	0.033	0.355**	-	-0.062	0.346*	-0.041	-0.176
TGW	0.087	-0.506**	-0.031	0.235	0.075	0.287	-0.228	-0.087	0.148	-	-0.308	-0.011	0.130
BY	-0.390*	-0.167	0.313	-0.580**	-0.845**	-0.140	0.056	0.060	0.664**	0.258	-	-0.527**	-0.121
GY	0.265	-0.244	0.121	0.687**	-0.076	0.134	0.109	-0.308	-0.176	0.190	0.256	-	0.928**
HI	0.352*	-0.316	-0.005	0.779**	0.205	0.214	0.034	-0.263	-0.315	0.096	-0.706**	0.972**	-

DH= Days to heading, FLA=Flag leaf area, DM= Days to maturity, PH= Plant height, SPM= Spikes m^{-2}, SL= spike length, SPS= Spikelets $spike^{-1}$, GPS= Grains $spike^{-1}$, GWS= Grain weight $spike^{-1}$, TGW= Thousand grain weight, GY= Grain yield, BY= Biological yield, HI= Harvest ind

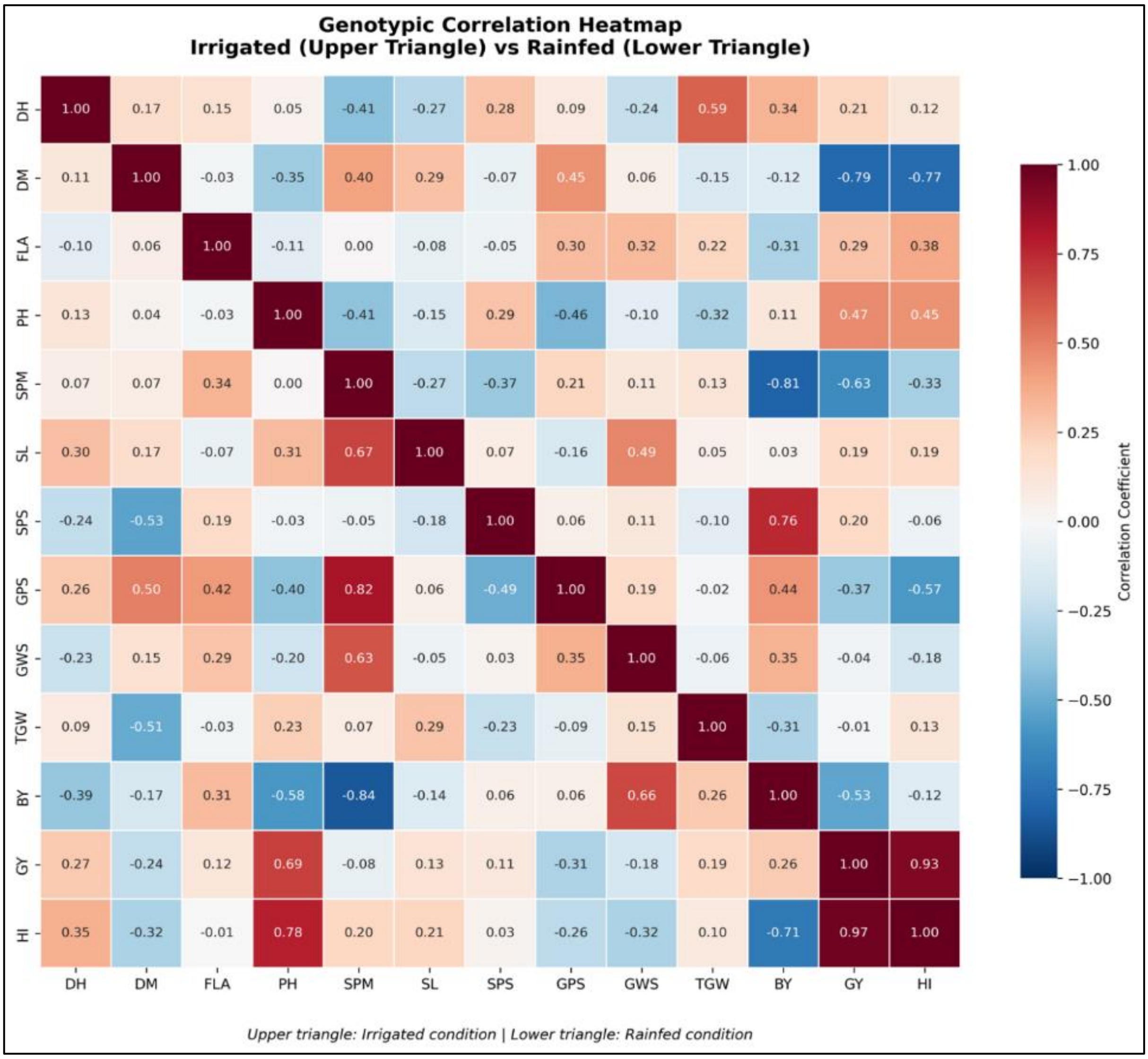

Figure 3: Genotypic correlation heatmap for 13 wheat traits under irrigated (upper triangle) and rainfed (lower triangle) environments. Correlation coefficients range from -1.00 (dark blue, negative) to +1.00 (dark red, positive). Trait abbreviations: DH = days to heading, DM = days to maturity, FLA = flag leaf area, PH = plant height, SPM = spikes m^{-2}, SL = spike length, SPS = spikelets $spike^{-1}$, GPS = grains $spike^{-1}$, GWS = grain weight $spike^{-1}$, TGW = 1000-grain weight, BY = biological yield, GY = grain yield, HI = harvest index.

Table 18: Phenotypic correlations for various yield and yield related traits of 32 wheat genotypes under irrigated (above diagonal) and rainfed (below diagonal) condition evaluated at the University of Agriculture, Peshawar during 2022-2023

Traits	DH	DM	FLA	PH	SPM	SL	SPS	GPS	GWS	TGW	BY	GY	HI
DH	-	-0.108	0.087	-0.146	-0.071	-0.294	0.162	0.002	-0.094	0.485**	0.183	0.037	-0.044
DM	0.015	-	-0.034	-0.372*	0.330	0.219	0.086	0.342	-0.009	-0.152	-0.070	-0.652**	-0.594**
FLA	-0.117	-0.010	-	-0.158	0.082	-0.064	-0.068	0.163	0.088	0.109	-0.151	0.207	0.241
PH	0.143	0.037	-0.012	-	-0.278	-0.153	0.158	-0.350*	-0.016	-0.310	0.020	0.347*	0.328
SPM	0.108	0.076	0.211	-0.016	-	-0.154	-0.221	0.173	0.035	0.143	-0.401*	-0.359*	-0.149
SL	0.274	0.101	-0.084	0.266	0.380*	-	0.001	-0.170	0.210	0.069	0.083	0.087	0.047
SPS	-0.159	-0.431**	0.220	-0.056	-0.151	-0.116	-	0.098	0.071	-0.053	0.501**	0.042	-0.176
GPS	0.233	0.311	0.330	-0.241	0.279	0.069	-0.241	-	0.111	-0.038	0.197	-0.351*	-0.449**
GWS	-0.100	0.136	0.225	-0.141	0.181	0.026	0.057	0.161	-	-0.109	0.007	-0.054	-0.055
TGW	0.124	-0.374*	0.085	0.199	0.156	0.284	-0.223	-0.007	0.042	-	-0.162	-0.023	0.058
BY	-0.149	-0.053	0.205	-0.382*	-0.338	-0.045	0.001	-0.040	0.349*	0.095	-	0.133	0.886**
GY	0.137	-0.195	-0.019	0.472**	0.079	0.020	0.130	-0.199	-0.046	0.116	-0.205	-	-0.335
HI	0.186	-0.134	-0.082	0.581**	0.187	0.078	0.095	-0.160	-0.136	0.087	0.941**	-0.510**	-

DH= Days to heading, FLA=Flag leaf area, DM= Days to maturity, PH= Plant height, SPM= Spikes m^{-2}, SL= spike length, SPS= Spikelets $spike^{-1}$, GPS= Grains $spike^{-1}$, GWS= Grain weight $spike^{-1}$, TGW= Thousand grain weight, GY= Grain yield, BY= Biological yield, HI= Harvest index

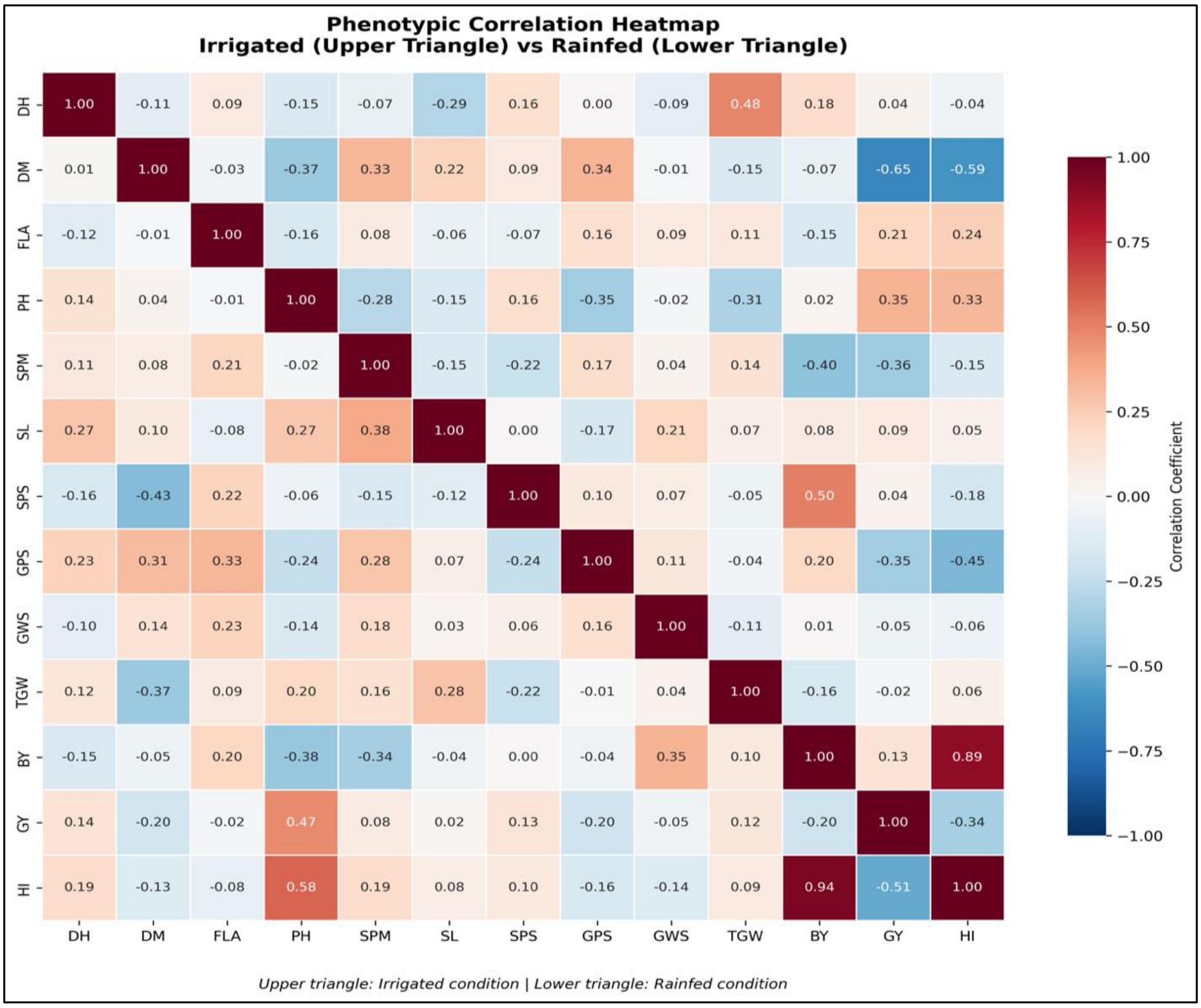

Figure 4: Phenotypic correlation heatmap for 13 wheat traits under irrigated (upper triangle) and rainfed (lower triangle) environments

Correlation coefficients range from -1.00 (dark blue, negative) to +1.00 (dark red, positive). Trait abbreviations as in Figure 1. Phenotypic correlations were generally weaker than genotypic correlations, reflecting environmental masking effects.

CONCLUSIONS AND RECOMMENDATIONS

The study demonstrates significant genetic variability among the 30 wheat genotypes evaluated under both irrigated and rainfed conditions. Drought stress was found to be a primary constraint, significantly reducing mean performance for all yield-contributing traits, including grain yield which decreased from 3705 kg ha^{-1} to 2508 kg ha^{-1}. Genotypes G-22 and G-30 were identified as highly stable and drought-tolerant across both environments, showing superior yield performance and resilience. The effectiveness of selection indices such as TOL, MP, YSI, SSI, and STI highlights their value in identifying genotypes that can maintain productivity under moisture-limited conditions.

Based on the results, genotype G-22 is recommended for widespread cultivation in both irrigated and rainfed regions of Peshawar and similar agro-climatic zones due to its high yield and stability. Future wheat breeding programs should prioritize the use of drought-tolerant lines like G-30 and G-13 as parental stock to develop new cultivars with enhanced resilience. Furthermore, the integration of stress selection indices, particularly STI and MP, into routine selection protocols is highly recommended to improve the efficiency of identifying drought-tolerant wheat varieties in arid and semi-arid environments.

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