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Fluctuation in Yield Parameters of Wheat Genotypes under Irrigated and Rainfed Conditions

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ABSTRACT

A collection of 24 different types of wheat genotypes, alongside four standard cultivars, underwent assessment in both irrigated and rainfed environments at Khyber Pakhtunkhwa Agricultural University Peshawar, Pakistan. To address the challenges posed by climate change, particularly drought, a randomized complete block design with three replications was implemented in both irrigated (non-stress) and rainfed (stress) environments. Analysis across these two conditions indicated significant variations ($P \le 0.01$) between the two systems for all traits except 1000-grain weight ($P > 0.05$). Furthermore, there was notable genetic diversity among the genotypes for all traits. Interaction between genotype and environment was particularly significant for tillers per square meter and grain yield exclusively. On average across the 28 wheat genotypes, reductions in tiller production, spike length, spikelets per spike, grains per spike, and grain yield under rainfed conditions were 117 per square meter, 0.8 centimeters, 2.0, 7.0, and 399 kilograms per hectare, respectively, compared to irrigated conditions. The high-yielding wheat genotypes under irrigated conditions were BVI(N)9 with 3446 kg per hectare, BII(N)1 with 3457 kg per hectare, and BIV(N)11 with 4410 kg per hectare, whereas under rainfed conditions they were BII(N)1 with 3236, BVI(N)12 with 3300, and BRF3 with 4007 kg per hectare. Heritability estimates were higher under non-stress conditions compared to stress conditions for all traits except grain yield, which remained stable across environments. Selection response, however, was more pronounced for all traits under non-stress conditions. Therefore, selecting under non-stress conditions is likely to yield better results compared to selecting under stress conditions.

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INTRODUCTION

During the 2020-21 period, Pakistan's wheat cultivation stood at a total of 27.50 million tons grown across and area of 9.178 million hectares, with an average yield of 2974 kg per hectare. Approximately 86.5% of the wheat cultivation area, totaling 7.88 million hectares, was irrigated, while the remaining 13.5%, equivalent to 1.29 million hectares, relied on rainfed conditions. (Agricultural Statistics of Pakistan, 2021-22). The average wheat yield nationally differed significantly between irrigated and rainfed systems, with 2974 kg per hectare and 1324 kg per hectare, respectively. This indicated a considerable decrease of 1560 kg per hectare (55.50%) under drought stress conditions. Figure 1 illustrates the disparity between the irrigated and rainfed conditions in Khyber Pakhtunkhwa. In total, the wheat cultivation area in Khyber Pakhtunkhwa spanned 761.8 thousand hectares, with 385.4 thousand hectares (50.6%) being rainfed and 376.4 thousand hectares (49.4%) being irrigated (Agricultural Statistics of Pakistan, 2021-22). In Khyber Pakhtunkhwa, the wheat grain yield averaged 2280 kg per hectare under irrigated regions and 1306 kg per hectare under rainfed regions, highlighting a significant disparity of 974 kg per hectare between the normal and water stressed conditions . Figure 1 illustrates a comparison of wheat production in Khyber Pakhtunkhwa over the past 11 years under both irrigated and rainfed conditions. The decrease in total wheat production compared to irrigated yield over the past 11 years varied from 16% to 41%, as depicted in Figure 2.

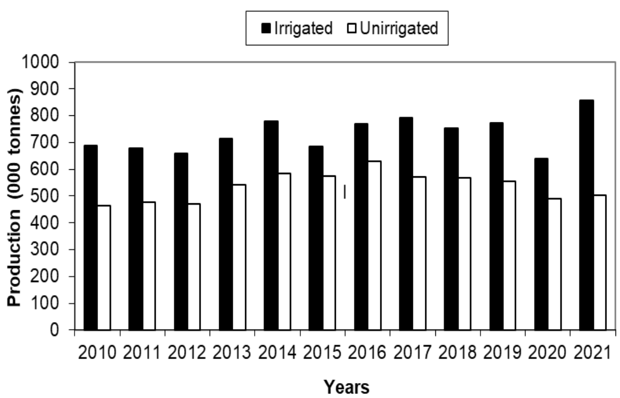

Figure 1. Average wheat yield of Khyber Pakhtunkhwa province under irrigated and rainfed regions (Agricultural Statistics of Pakistan, 2021-22).

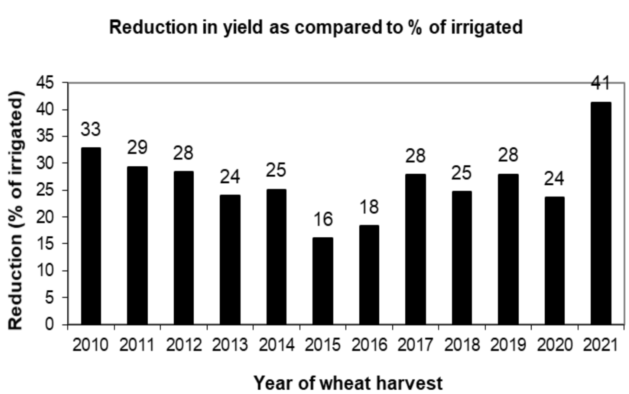

Figure 2. Reduction in wheat yield of Khyber Pakhtunkhwa province under rainfed (as percentage of irrigated) condition (Agricultural Statistics of Pakistan, 2021-22).

This underscores the urgent necessity to develop wheat genotypes capable of thriving under both irrigated and rainfed conditions to bridge the yield gap between the two systems. In this context, evaluating trait variation, estimating heritability, and identifying suitable selection environments are crucial steps in breeding programs aimed at narrowing the yield gap and ensuring wheat security in Pakistan.

The genetic enhancement of wheat yield under water stress often relies on assessing heritability estimates for various yield-contributing traits. Heritability, which is derived from variances observed in early generations and advanced lines, provides valuable insights into the extent of genetic transmission across successive generations. This assists breeders in making informed selections, as emphasized by Allard in 1960. Accurate estimation of heritability is crucial for breeders to anticipate the genetic potential of breeding materials, identify promising hybrid combinations, and determine effective selection methods, as demonstrated by research conducted by Hamblin *et al*. in 1980 and Sukumaran *et al*. in 2018. Higher heritability estimates streamline the selection process, reducing time and complexity while enhancing genetic improvement.

However, selecting for traits under drought stress presents challenges due to low heritability, variable testing conditions, and substantial genotype-by-environment interactions (Hamblin *et al.,* 1980, Guttieri, 2020). Modern plant breeding approaches are aiming to develop crops that are not only resource-efficient under stressful conditions like drought, but also highly productive when conditions are favorable. This two-pronged approach, combining stress tolerance with high yield potential, is a recent advancement in breeding strategies (Braun *et al*., 1992; Ginkel *et al*., 1998; Mondal *et al*., 2016). Consequently, efforts have been directed towards evaluating morphological and yield trait variations in wheat under both irrigated and rainfed conditions. The objective of this study is to determine heritability estimates for yield and associated traits and to identify the most favorable environments for trait selection. In pursuit of this aim, we undertook an assessment of the diversity in morphological and yield traits of wheat under both rainfed and irrigated conditions. Our objective was to evaluate the heritability estimates for yield and associated traits and determine the environments most suitable for the selection of particular traits.

MATERIALS AND METHODS

The study was conducted at The University of Agriculture, Peshawar, and involved the evaluation of twenty-four advanced wheat lines obtained from the Cereal Crops Research Institute (CCRI), Pirsabak, Nowshehra, along with four check cultivars. These evaluations were carried out in separate experiments under both irrigated and rainfed conditions. The evaluated wheat genotypes included B-RF 1, B-II (N) 1, B-IV (N) 1, B-II (N) 3, B-RF 3, B-VI (N) 3, B-VI (N) 5, B-IV (N) 6, B-VI (N) 6, B-RF 7, B-VI (N) 8, B-RF 8, B-VI (N) 9, B-IV (N) 10, B-IV (N) 11, B-VI (N) 12, B-RF 15, B-RF 17, B-III (N) 17, B-IV (N) 16, B-IV (N) 17, B-VI (N) 16, B-VI (N) 17, and SAWYT-50. The four check cultivars were Pirsabak-2005, Pirsabak-2008, Saleem-2000, and Suleman 96, with Suleman 96 recommended for rainfed, Saleem 2000 and Pirsabak 2008 recommended for irrigated, and Pirsabak 2005 is recommended for both environments in Khyber Pakhtunkhwa.

Using a randomized complete block design with three replications in both systems, the experiments were conducted adjacent to each other to minimize environmental bias. Notably, the rainfed experiment only received the rain water with no irrigation during the growing season. Each genotype plot consisted of 3 rows measuring 3 meters and spaced 0.30 meters apart. The experiment was planted in late October and the seed rate used was 110 kg ha^{-1}. The basic fertilizers, nitrogen and phosphorus were applied at rates of 120:60 (kg ha^{-1}) for irrigated experiments and 60:30 (kg ha^{-1}) for rainfed experiments, respectively. Fertilizer application was split in irrigated plots but applied as a single dose at sowing for rainfed plots.

Statistical analysis was conducted separately for both water regimes (Table 1) to calculate genetic and environmental proportions of variances, which were then used to calculate broad-sense heritabilities for various traits. This analysis followed the method outlined by Singh and Chaudhery in 1997. Recent research emphasizes the importance of comprehensive statistical analyses to assess genetic and environmental contributions accurately (Guttieri *et al.,* 2020; Sukumaran *et al.,* 2018). Additionally, the selection of appropriate experimental designs and methodologies ensures robust evaluation of wheat breeding programs (Mondal *et al.,* 2016). These advancements enhance the reliability of genetic parameter estimation, aiding in the development of wheat varieties resilient to diverse production environments.

Table 1. Analysis of variance for 28 wheat genotypes under each production system for computing genetic and environmental variances of various traits.

Source of variation	Df	MS	Expected mean squares
Replication	2	---	---
Genotypes	27	M_1	$V_e + rV_g$
Error	54	M_2	V_e

Where:

Genetic variance = $V_g = \dfrac{M_1 - M_2}{r}$

Environmental variance = $V_e = M_2$

Heritability = $h^2_{BS} = \dfrac{V_g}{(V_g + V_e / r)} = \dfrac{V_g}{V_p}$

Expected response (Re) for important traits was predicted under each production system using specific selection intensity as under.

Selection response (Re) = $i \times \sqrt{V_p} \times h^2{}_x$

Where:

i = A constant value at specific selection intensity

V_p = Phenotypic variance for a trait under a specific production system

h^2_x = Heritability for trait x in a specific production system

RESULTS AND DISCUSSION

Tiller Production in Wheat Genotypes under Drought Stress

Significant differences ($P \leq 0.01$) in tillers per square meter were observed among genotypes, environments (irrigated vs. rainfed), and their interaction, as indicated in Table 2 using Analysis of Variance. Notably, drought stress led to a notable reduction in tillering, a crucial yield-contributing trait. Such reductions have been extensively documented by numerous researchers (Rickman & Keppler, 1991; Riaz, 2003). This phenomenon can be attributed to plants prioritizing reproductive stage under moisture limitations, leading to reduced vegetative growth and tillering. Additionally, the significant genotype × environment interaction underscores the unstable nature of tillering across the two environments.

The observed average coefficient of variation of 12.98% across environments for tillers m^{-2} reinforces this instability. Additionally, genotypic variation was substantially greater under irrigated conditions compared to rainfed conditions (Table 3). These findings align with previous reports by Eid (2009) and Naserian *et al*. (2007), who documented significant drought-induced reductions in spikes m^{-2}. Importantly, tillers m^{-2} displayed high heritability under irrigated conditions, but only moderate heritability under rainfed conditions (Table 4). This finding implies a stronger genetic influence on tillering under favorable moisture conditions, leading to a potentially more effective selection process. Selection differential and expected response values also reflect this trend, emphasizing the greater potential for improvement through selection under irrigated conditions. This aligns with the observations of Necker *et al*. (1993), who highlighted the combined influence of genetic and environmental factors on tillering, resulting in variable responses under different climatic conditions.

Considering the direct relationship between tillers m^{-2} and grain yield, maximizing tillering potential translates to potentially higher yields. Genotypes BRF8, BIV(N)1, and BIII(N)1 displayed the highest tillering capacities under irrigated conditions, while BIV(N)1, SAWT50, and BIV(N)11 excelled under rainfed conditions (Figure 3). In drought-prone environments, prioritizing genotypes with stable tillering performance across varying moisture conditions would be crucial for yield sustainability. Recent literature emphasizes the importance of drought tolerance mechanisms in wheat breeding programs. For instance, Guo *et al*. (2023) identified quantitative trait loci (QTLs) associated with drought-tolerant tillering in wheat, highlighting the potential for marker-assisted selection in breeding efforts. Additionally, Shi *et al*. (2022) explored the role of root traits in enhancing drought tolerance and tillering potential.

Table 2. Coefficient of variation (CV) and Mean squares (MS) for yield and yield contributing traits of 28 wheat genotypes grown under rainfed and irrigated production systems.

Sources	Degrees of freedom	Tillers m^{-2}	Spike length	Spikelets $spike^{-1}$	Grains $spike^{-1}$	1000-grain weight	Grain yield
Environments (E)	1	15812.57**	26.56**	873.15**	1981.72**	17.42^{NS}	17759302.88**
Reps w/n env.	4	14963.94	11.5	21.76	528.65	224.85	87876.67
Genotypes (G)	27	573885.48**	2.37**	7.37**	155.29^{NS}	76.76**	402489.37**
G x E	27	10136.21**	0.41^{NS}	1.08^{NS}	84.9^{NS}	10.36^{NS}	216877.84**
Error	108	3622.37	0.57	1.45	61.51	19.71	234373.75
CV (%)		12.98	6.90	5.71	14.26	12.21	7.99

Table 3. Heritability and Environmental (Ve) and Genetic (Vg) variances for various traits of 28 wheat genotypes evaluated under rainfed and irrigated environments.

Parameters	Irrigated			Rainfed		
	V_g	V_e/r	h^2_{BS}	V_g	V_e/r	h^2_{BS}
Tillers m^{-2}	5697.48	1069.65	0.84	537.20	1345.26	0.29
Spike length	0.41	0.20	0.67	0.14	0.18	0.43
Spikelets $spike^{-1}$	1.27	0.40	0.76	0.58	0.56	0.51
Grains $spike^{-1}$	27.70	26.81	0.51	11.36	14.20	0.44
1000 grain weight	9.76	4.63	0.68	6.14	8.51	0.42
Grain yield	114234.59	19048.44	0.86	153230.01	18018.11	0.89

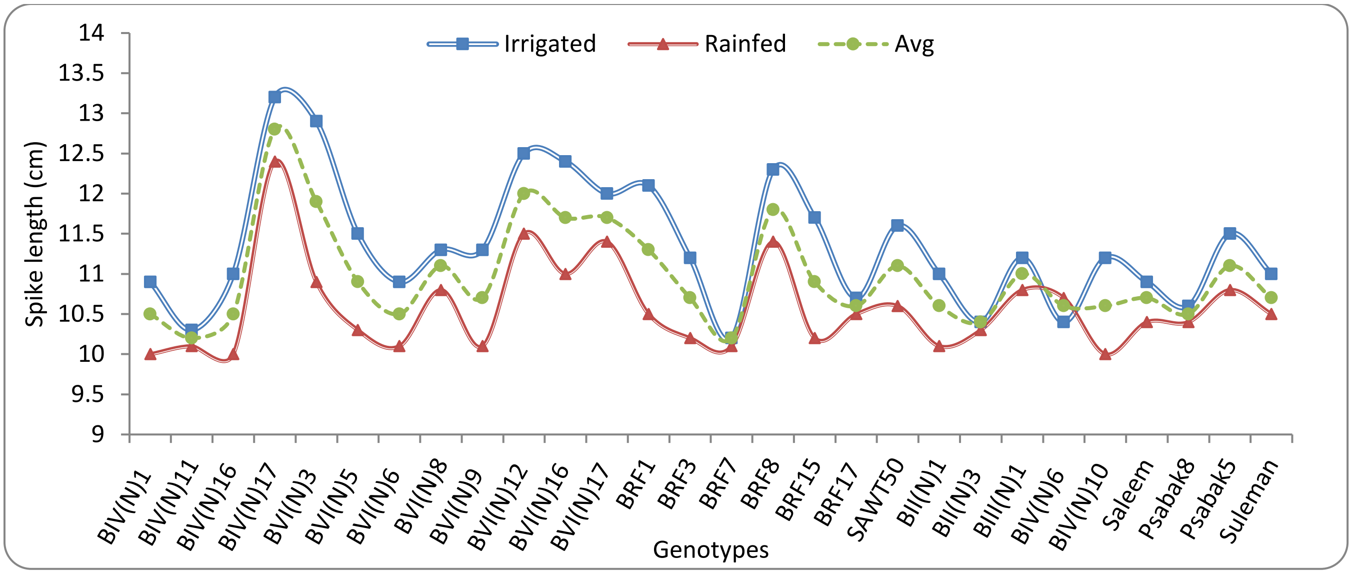

Figure 3. Means of 28 wheat genotypes evaluated under irrigated and rainfed environments for spike length at the University of Agriculture, Peshawar.

Spike Length Stability Across Environments

The combined analysis of variance (ANOVA) showed highly significant differences ($P \leq 0.01$) in spike length between irrigated and rainfed environments, as detailed in Table 2. Additionally, genotypic variation was found to be highly significant. However, there was no significant genotype × environment interaction observed in relation to spike length. This lack of interaction suggests stability in spike length across the two production systems for the tested wheat genotypes. These findings align with observations by Iqbal *et al*. (1999), Kalinin (1988), and Saleem (2003), who documented significant reductions in spike length due to water stress during vegetative and flowering stages. However, Swati *et al*. (1985) reported relatively stable spike length across diverse environments. This potential discrepancy could be attributed to variations in the timing and severity of drought stress, as well as the developmental stage of the crop at the time of stress exposure. Among the genotypes, BVI(N)3, BVI(N)12, and BIV(N)17, displayed the largest spikes under irrigated conditions, while BIV(N)17, BRF8, and BVI(N)17 excelled under rainfed conditions (Figure 4).

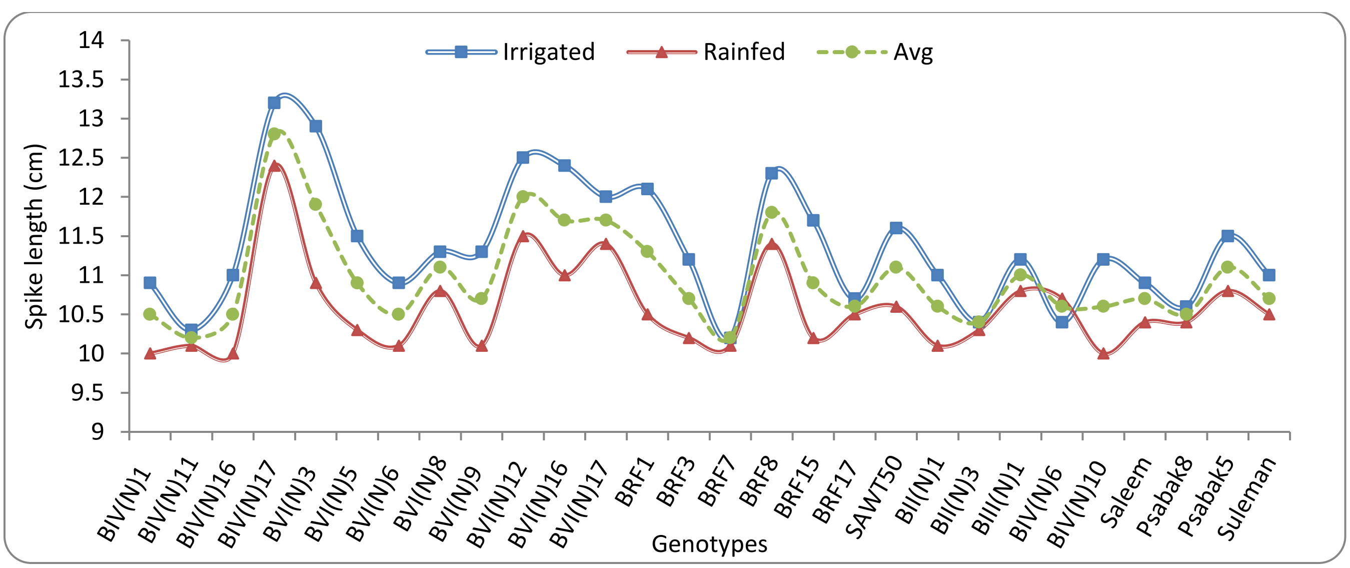

Figure 4. Means of 28 wheat genotypes evaluated under irrigated and rainfed environments for spike length at the University of Agriculture, Peshawar.

Notably, BIV(N)17 exhibited consistent performance across both environments, highlighting its potential for broader adaptability. The observed higher heritability of spike length under irrigated conditions compared to rainfed conditions (Table 3) aligns with findings by Prodanovic (1993) and Subhani & Chawdhery (2000). This suggests a stronger genetic influence on spike length under favorable moisture conditions, potentially leading to more effective selection for this trait. The greater expected response under irrigated conditions (Table 4) further reinforces this notion.

Table 4. Here are the means of the whole population ($\overline{X}$), selected lines ($\overline{X_s}$), and check cultivars ($\overline{X_c}$), as well as the selection differential (S), expected response (Re), and selected genotypes for yield and yield-related traits under irrigated and rainfed conditions.

Traits	Environments	$\overline{X}$	$\overline{X_s}$	$\overline{X_c}$	S	Re	Top four ranking genotypes using 15 % selection intensity
Tillers m^{-2}	Irrigated	522	658	534	136.0	114.50	BRF8, BIV(N)1 BIII(N)1, BVI(N)
	Rainfed	405	461	430	56.0	15.98	SAWT50, BIV(N)1, BRF1, BIV(N)11
Spike length (cm)	Irrigated	11.4	12.7	11.0	1.3	0.87	BVI(N)3, BIV(N)17, BVI(N)12, BVI(N)16
	Rainfed	10.6	11.7	10.5	1.1	0.47	BVI(N)12, BIV(N)17 BVI(N)17, BRF8
Spikelets $spike^{-1}$	Irrigated	22	24	21	2.0	1.52	BVI(N)12, BIV(N)17 BIII(N)1, BIV(N)6
	Rainfed	20	21	20	1.0	0.51	BIV(N)17, BIV(N)11 BVI(N)12, BVI(N)17
Grains $spike^{-1}$	Irrigated	59	77	61	18.0	9.15	BRF1, BVI(N)3 BIV(N)12, BRF15
	Rainfed	52	58	53	6.0	2.67	BIV(N)11, BVI(N)16 BVI(N)12, BIV(N)16
1000 grain weight (g)	Irrigated	36.0	41.0	34.7	5.0	3.39	BRF3, BVI(N)12 BVI(N)16, BRF15
	Rainfed	36.7	40.9	38.4	4.2	1.76	BVI(N)12, BRF3 BIV(N)17, BVI(N)16
Grain yield (kg ha^{-1})	Irrigated	3152	3686	3292	534	457.68	BII(N)1. BIV(N)11 BVI(N)9, BVI(N)8
	Rainfed	2753	3378	2898	625	559.24	BRF3, BVI(N)12 BII(N)1, BIV(N)17

Recent literature emphasizes the importance of exploring drought-tolerant mechanisms affecting spike development. For instance, Xu *et al*. (2020) identified quantitative trait loci (QTLs) associated with drought-tolerant spike length in wheat, showcasing the potential for marker-assisted selection in breeding programs. Additionally, Chen *et al*. (2022) investigated the role of genes regulating plant hormones and signaling pathways in modulating spike development under water stress.

Spikelets Spike^{-1}: Stability and Selection Potential under Diverse Environments

Pooled analysis of variance (ANOVA) for spikelets spike-1 revealed highly significant (P ≤ 0.01) main effects of environment and genotype, but a non-significant genotype × environment interaction (Table 2). This lack of interaction indicates remarkable stability of this crucial trait across irrigated and rainfed environments for the tested wheat genotypes. Notably, genotypes under irrigated conditions exhibited significantly higher

spikelet counts compared to rainfed conditions. This phenomenon can be attributed to early drought stress during development, leading to floret death at both distal and basal ends of the spike (Kirby & Appleyard, 1984).
Our findings align with reports by Qadir *et al*. (1999), who documented similar reductions in spikelets due to water stress during vegetative and reproductive stages across various wheat varieties. Additionally, Fethi & Mohamed (2010) confirmed genotypic variations in spikelet number. Heritability estimates for spikelets per spike were found to be intermediate under stress conditions and low under non-stressed conditions, as presented in Table 3. This implies a moderate genetic influence on the trait under drought stress, but a weaker influence under favorable moisture conditions. Interestingly, genotypes BIV(N)17, BVI(N)12, and BIII(N)1 maintained consistently high spikelet numbers across both environments (Figure 5), highlighting their potential for broader adaptability.
The selection differential and expected response for spikelets spike-1 were significantly higher under non-stressed conditions compared to stressed conditions (Table 4). This suggests that selection based on this trait would be more effective in well-watered environments, potentially due to the stronger genetic influence observed under those conditions. Recent literature emphasizes exploring drought-tolerance mechanisms impacting floret development and spikelet formation. For instance, Liu *et al*. (2023) identified drought-responsive genes associated with spikelet development through transcriptome analysis in wheat, offering potential targets for genetic manipulation in breeding programs. Additionally, Yang *et al*. (2023) investigated the role of plant hormones in regulating floret survival and spikelet abortion under water stress, providing insights into potential breeding strategies.

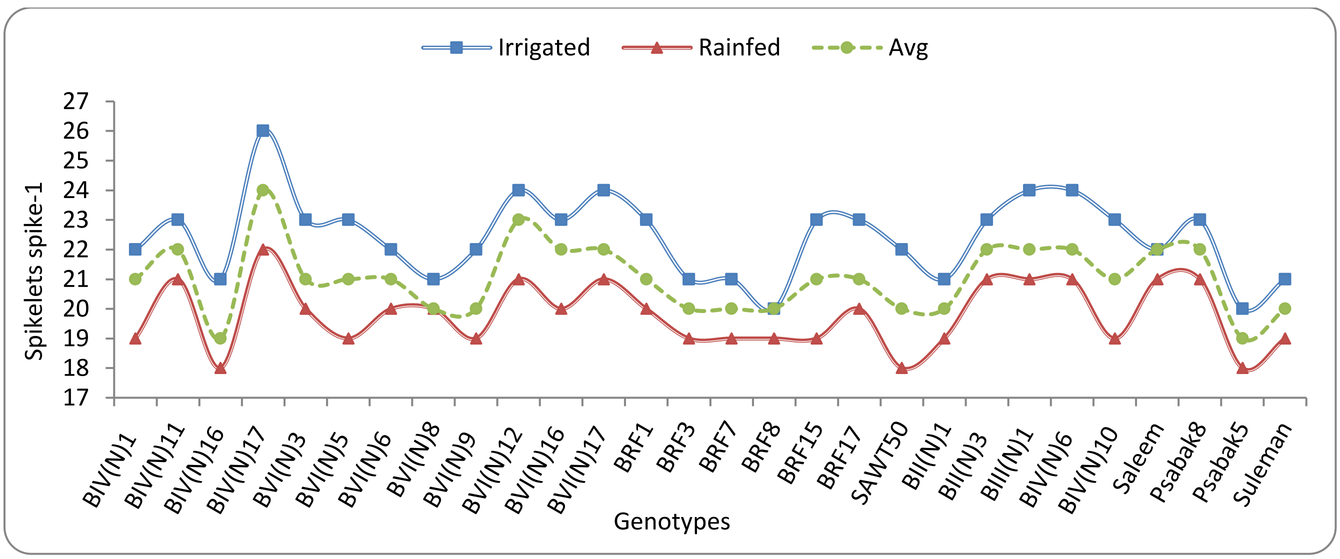

Figure 5. Means for spikelets spike-1 of 28 wheat genotypes evaluated under irrigated and rainfed environments at The University of Agriculture, Peshawar .

Grains Spike-1: Stability and Selection Potential under Drought Stress

The pooled analysis of variance (ANOVA) indicated highly significant differences ($P \leq 0.01$) between irrigation environments for the number of grains per spike^{-1}. However, neither genotype nor genotype × environment interaction showed significant effects. (Table 2). This suggests a strong environmental influence and remarkable genotypic stability for this crucial yield component across irrigated and rainfed conditions. As expected, water stress significantly reduced grain number, likely due to early drought stress leading to basal and distal floret death (Kirby & Appleyard, 1984).
The lack of significant genotype × environment interaction aligns with the recommendation of Shpiler & Blum (1991) to prioritize this trait for drought-tolerant wheat breeding due to its stability across diverse environments. Interestingly, the absence of significant genotypic differences indicates potential limitations in the current germplasm pool for this trait. Moderate heritability estimates under both irrigated and rainfed conditions (Tables 2 & 3) suggest a moderate genetic

basis for grain number, offering opportunities for improvement through selective breeding. However, the significantly higher selection differential and expected response under non-stressed conditions highlight the potential for faster genetic gains in favorable environments. This emphasizes the importance of considering both heritability and selection pressure when designing breeding strategies.

Genotypes BRF1 and BIV(N)3 displayed superior grain number under irrigation, while BIV(N)11 and BVI(N)16 excelled under rainfed conditions (Figure 6). These genotypes warrant further investigation for their potential contributions to drought-tolerant breeding programs. Recent research emphasizes exploring mechanisms underlying drought tolerance and grain number stability. For instance, Liu *et al*. (2023) identified drought-responsive genes associated with floret development and grain filling through transcriptome analysis in wheat, offering potential targets for genetic manipulation. Additionally, Xu *et al*. (2022) investigated the role of root traits in enhancing drought tolerance and grain number, providing insights into potential breeding strategies.

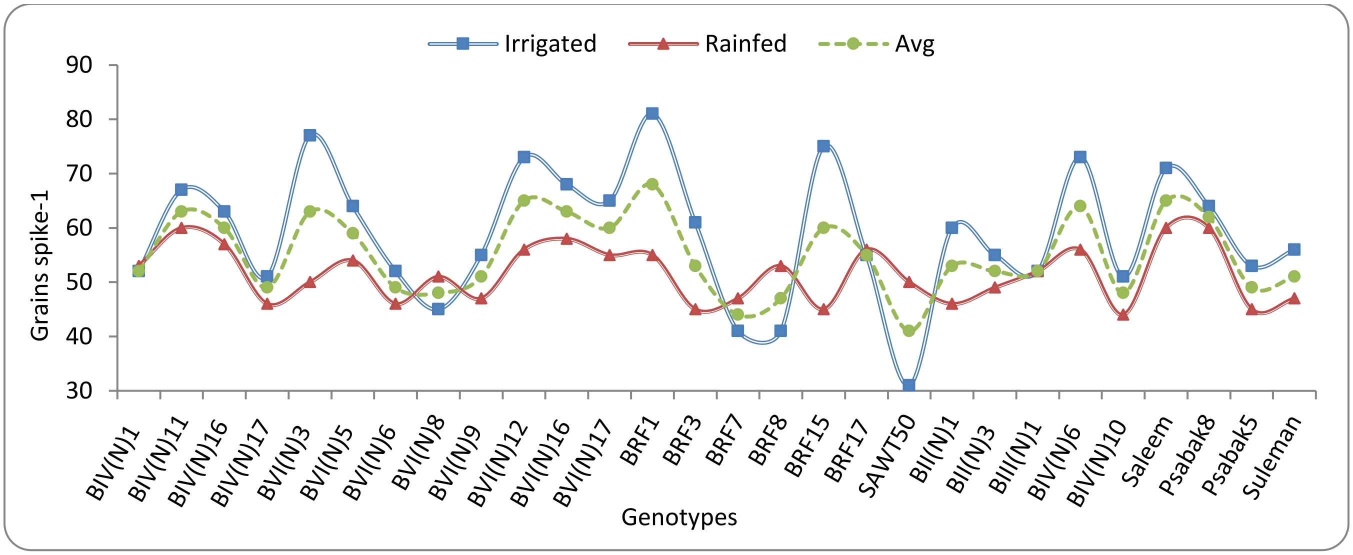

Figure 6. Means of 28 wheat genotypes evaluated under irrigated and rainfed environments for Grains spike-1 at The University of Agriculture, Peshawar.

Thousand-Grain Weight: Unveiling Stability and Selection Potential under Diverse Environments

Combined analysis of variance (ANOVA) revealed highly significant ($P \leq 0.01$) genotypic differences for thousand-grain weight, but no significant effects for environment or genotype × environment interaction (Table 2). This implies remarkable stability of this crucial yield component across irrigated and rainfed conditions, suggesting negligible environmental influence on genotypic performance for thousand-grain weight. Interestingly, the mean grain weight even increased slightly (2%) under stress, potentially due to reduced tillering leading to greater resource allocation per remaining grain.

Our findings align with reports by Afiuni *et al*. (2006), Kirwigi *et al*. (2004), Guinata *et al*. (1993), and Zhong-hu & Rajaram (1994), who documented limited environmental impact on thousand-grain weight. However, Riaz (2003) suggests potential reductions under severe drought, highlighting the importance of considering stress severity and timing. Early stress in our study, as observed in Figure 2, might explain the observed stability by impacting tillering rather than directly affecting individual grain weight. Moderate heritability under irrigation and low heritability under rainfed conditions (Table 3) suggest some genetic influence on thousand-grain weight in both environments, but a stronger response to selection under favorable moisture conditions. This aligns with the double expected response observed under irrigation compared to rainfed conditions (Table 4), emphasizing the potential for faster genetic gains in stress-free environments.

Genotypes BRF3 and BVI(N)12 consistently produced heavier grains across both production systems (Figure 7), highlighting their potential for breeding programs seeking stable and high-yielding genotypes. Recent research delves deeper into understanding drought tolerance mechanisms affecting grain weight. For instance, Chen *et al*. (2022) identified drought-responsive genes associated with grain filling and endosperm development in wheat using transcriptome analysis, offering potential targets for genetic manipulation. Additionally, Pandey *et al*. (2023) investigated the role of plant hormones in regulating grain weight under water stress, providing insights into potential breeding strategies.

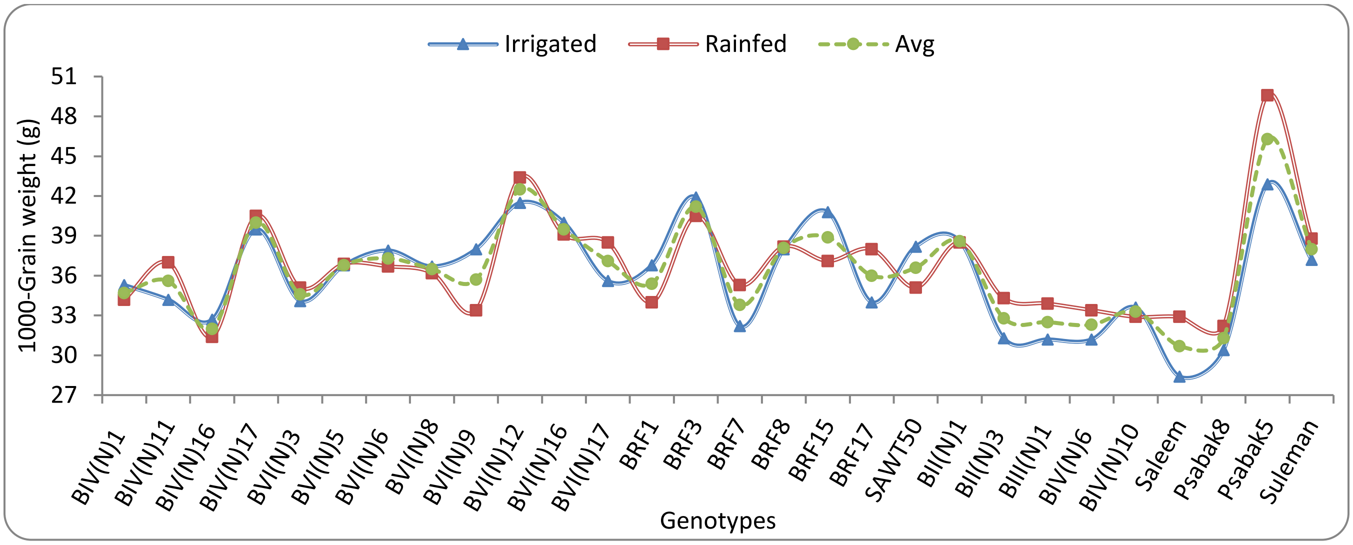

Figure 7. Means of 28 wheat genotypes evaluated for 1000-grain weight under irrigated and rainfed environments at The University of Agriculture, Peshawar.

Grain Yield: Deciphering Genotypic Responses and Breeding Strategies under Drought Stress

Combined analysis of variance (ANOVA) revealed highly significant ($P \leq 0.01$) main effects for environment, genotype, and genotype × environment interaction for grain yield (Table 2). This confirms significant yield reduction under drought stress and differential responses among genotypes, highlighting the complex nature of drought tolerance and the need for multi-environment testing.

Our findings align with Sadiq *et al*. (1994) who emphasized the interplay between yield potential and stress response in determining performance under drought. Additionally, Naserian *et al*. (2007) highlighted the influence of genotype and stress timing on yield reduction. While Fisher & Wood (1979) associated higher stress tolerance with greater pre-stress dry matter accumulation, other studies (Sayrae *et al.,* 1997; Araus *et al.,* 2002) emphasized the importance of increased assimilate allocation to kernels. Our data suggest a dominant effect of drought stress on yield reduction (Dencic *et al.,* 2000), highlighting the need for breeding strategies specific to challenging environments.

Interestingly, despite moderate heritability estimates reported by Golabadi *et al*. (2005) under both optimal and stressed conditions, our study observed high heritability across environments (Table 3). This suggests potential for effective selection under both irrigated and rainfed conditions. Furthermore, the higher expected response under stress (Table 4) due to higher selection differential and stable heritability is counterintuitive and requires further investigation.

Genotypes BII(N)1, BIV(N)11, and BVI(N)9 performed best under irrigation, while BRF3, BII(N)1 , and BVI(N)12 excelled under rainfed conditions (Figure 8). This highlights the importance of multi-environment testing and the potential for identifying genotypes with specific adaptation profiles. Recent research explores genetic and physiological mechanisms underlying drought tolerance and yield stability. For instance, Li *et al*. (2023) identified drought-responsive QTLs associated with grain filling and stress tolerance using genome-wide association studies in wheat, offering potential targets for marker-assisted breeding. Additionally, Lastochkina, *et al*. (2023) investigated the role of plant hormones in regulating assimilate partitioning and stress response, providing insights into potential breeding strategies for enhancing yield under drought.

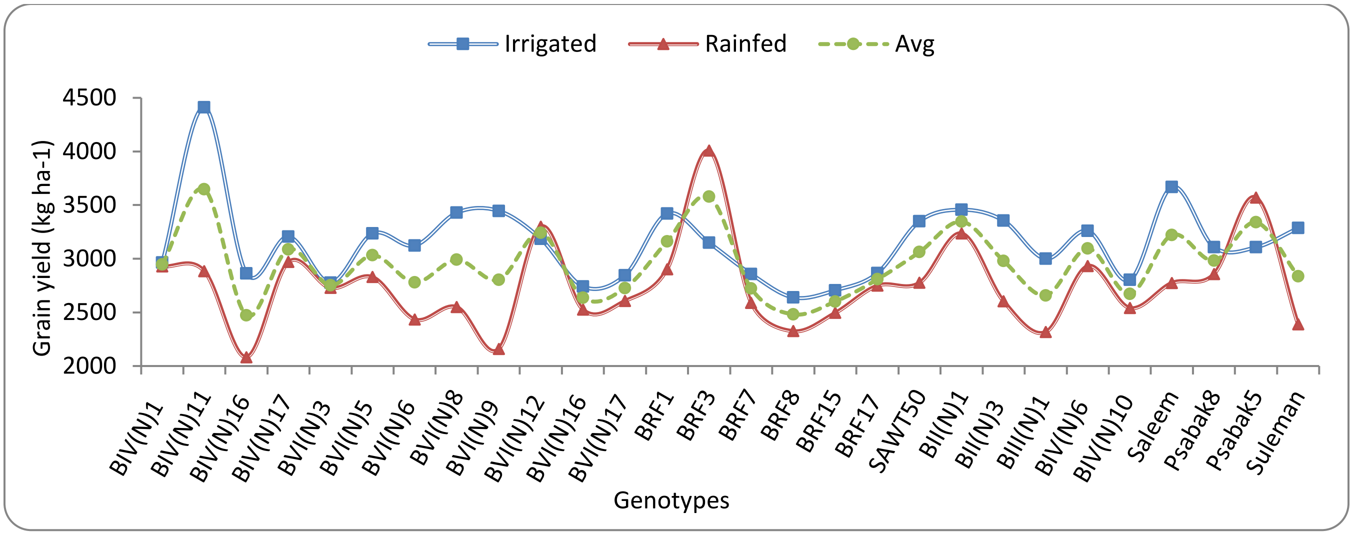

Figure 8. Means of 28 wheat genotypes evaluated for grain yield under irrigated and rainfed environments at The University of Agriculture, Peshawar.

CONCLUSION

The current study revealed significant reductions in tillering, spikelets, grains, and yield, underlining the detrimental effects of drought on productivity. While genotype x environment interactions highlighted the need for multi-environment testing and location-specific strategies, promising genotypes like BIV(N)17 and BVI(N)12 displayed consistent performance across traits. Moderate heritabilities across environments suggest potential for selection-based improvement, particularly for grain yield under stress, where higher expected response necessitates further investigation.

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