Research Article

Phenological Assessments of Selected Wheat Genotypes in Different Agro-Environment

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Abstract | Despite the genetic potential, the yield performance of a genotype is expressed in the prevailing environments. A high yielding genotype may not necessarily reflect its potential performance when subjected to a different Agro-Environment (AE). This study, therefore, aimed to assess the foremost developmental stages of the selected genotypes of wheat in three AE *i.e.* AEP (Peshawar), AEK (Kashmir) and AEC (Chitral). An experiment was conducted in a randomized complete block, having 3 replications. Four cultivars (*i.e.* Pirsabak-2005, Pakhtunkhwa-2015, Pakistan-2013 and DN-84) along with three advanced lines (i.e. P-2, P-12 and P-18) were compared for the crop growth seasons (i.e. 2017-18 and 2018-19). Averaged across genotypes, days to emergence, heading, anthesis, and maturity did differ ($p<0.05$) in various AE, with highest in higher altitudes and lowest in the plains area. Genotypes differed in crop developmental stages with mild to marked effects on tiller height, spike length, spike weight and unit grain weight, which has resulted in significant changes ($p<0.05$) for biomass and grain yield. Harvest indices did differ for AE among genotypes. Based on the experimental results, it is concluded that a genotype may not necessarily perform similar in production with changing the AE. However, with a close association of the crop developmental stages, more than one genotype can be recommended to perform good within different AE to adress future food security. Moreover, expressing suitable traits, a genotype could be used as a source of well breeding material for ensuring food security in changing climate.

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Introduction

Wheat (*Triticum aestivum* L.) is an important staple food crop of the poor people in the world (Pandey *et al.*, 2020). Its grains are rich source of energy and carbohydrates, which provides components essential for health i.e. protein, vitamins, dietary fibers (Bhutto et al., 2021). Its demand increases in developing countries due to its higher consumption with increasing population (Zandalinas *et al.*, 2018). Climate change is an emerging challenge to crops, which may increase or decrease its production in different agro-ecological zones (Raza *et al.*, 2019). Temperature rise boosts growth of wheat from sowing to maturity, but humidity together encourages scale of rust and smut attack (Rezaei *et al.*, 2018). Rise in temperature tended to continue at the start of this century and is expected to increase, which makes sense to understand the wheat crop phenology in different environments. A minor change in climate, specifically at anthesis stage of the crop growth, has resulted in a complete grain failure (He *et al*., 2020). Unavailability of irrigation or rain at sowing time has shifted wheat sowing from normal to late in season (Akmal *et al*., 2018), which results in a limited reproductive stage that adversely affects the harvest index (Gobin, 2018).

Other than production factors, temperature plays a key role in crop growth and development (Awan *et al*., 2017a). Temperature fluctuations correspond to the plant development have shown significant effects on production of wheat (Zhao *et al*., 2017). It is reported that high temperature may lower downs photosynthesis by reducing metabolism and oxidation of chloroplasts, which adversely affects the yield (Wang *et al*., 2018a). To turn a genotype to mature faster may be due to a rapid increase in temperature, which resulted in a reduction in production (Khan *et al*., 2021). Increase in temperature for a while i.e. a few hours may not be harmful but adversely affects productivity (IPCC, 2012). Studies have paid attention to extreme events, such as temperature shock at grain development stages focusing on yield (Ali *et al*., 2017). Crop response differently to different environments either by fluctuation in temperature or drought stress events during the crop development (Cohen *et al*., 2021). Variations in environment are due to changes in temperature (i.e. the photoperiod and intensity at a given time), which coupled with drought stress responded accordingly for rates of the crop evapotranspiration to contribute to growth (Phan *et al*., 2018).

Wheat is originated in southwestern Asia. It is an important staple food crop of central Asia including Pakistan (Liu *et al*., 2017a). Wheat occupied the maximum area under cultivation for the protein source (FAO., 2020). It has a broad range of adaptability to a different environment (Dowla *et al*., 2018), But still the climatic changes govern its performance for different genotypes. This is due to both biotic and abiotic factors *e.g*. salinity, temperature, soil water, *etc*. Genotypes released with either by single plant selection or inter-breeding of selected plants for different traits. Both single plant selection and interbreeding have shown equally good performance in fields in different environments. Nontheless, genotype performed better in an AE after its release but the sustainability not ensured under mild changes permanently (Osei *et al*., 2018)

Keeping in view the future food security, it is important to compare the developmental stages of genotypes for good traits identification, which can be used as breeding material for changing climate of an AE. The study, therefore, aimed to compare developmental stage of the crop growth in different AE focusing on phenological differences of genotypes. We, therefore, compared growth performance of selected genotypes in different AE to recommend a genotype wider cultivation ensured food security.

Materials and Methods

Experimental sites and locations

Experiments were conducted in three agro-environment (AE) focusing on the objective to assess phenological changes during the crop growth and development for two seasons. Three AE were the University of Agriculture Peshawar (AEP), the Agriculture Research station Garhi-Dopatta Azad Kashmir (AEK), and the Agriculture Research station Bunni, Chitral (AEC). According to USDA classification, the soil type of the three AEP ranked halpic luvisol, alkaline clay-loam and contains organic matter 10.94 g kg-1 (Anonymous 2007). Whereas, AEK falls within Himalayan orogenic belt and the soil has a pH of 6.5 to 7.5, clay loam texture, adequate organic matter, available Phosphorus and Potassium (Almas and Saeed, 2000). Soil of the AEC (Chitral-Bunni) ranges from silt-loam, slightly acidic and moderate to highly calcareous with salinity indication in patches and organic matter >2% (Ahmad *et al*., 2018) Location and the crop growth factors of the different AE are shown in Table 1. However, diurnal temperatures (Max. and Min.) and rainfall of the crop growth seasons are shown in Figure 1.

Experimental design and treatments

Experiments were randomized complete block, in three replications at each AE with a common layout, which includes a set of seven genotypes of which 4 were high yielding cultivars (*i.e*. Pakhtunkhwa-2015, Pakistan-2013, Pirsabak-2005, & DN-84) and three were the advanced lines (i.e. P-2, P-12, & P-18). The pre-basic seed-class was used at the rate of 100 kg ha^{-1} and a hand-driven drill on November 30 (2017), and 10 (2018) in AEP, November 27 (2017), and 21(2018) in AEK, October 13 (2017), and 12 (2018) in AEC. There were six rows of 5.0m length equally spaced at 30cm width. The field was irrigated and

Table 1: *Comparison of agro-environment for different climate and locations.*

Agro-environment	Height above sea level	Temperature (^{O}C)		Rainfall (mm)	Latitude & altitude	Irrigation with rainfall (mm)
		Max.	Min.			
AEP (Peshawar)	350	40.7±6.29	24±6.24	500-700	34.01°N & 71.52 °E	607* +602**
AEK (Kashmir)	819	20 to 32	04 - 07	1242	34.22 °N & 73.61 °E	576*+815**
AEC (Chitral)	1880	11.4-32.8	11.4	800	36.27 °N & 72.25 °E	606*+500**

** represents 2017-18 and **2018-19*

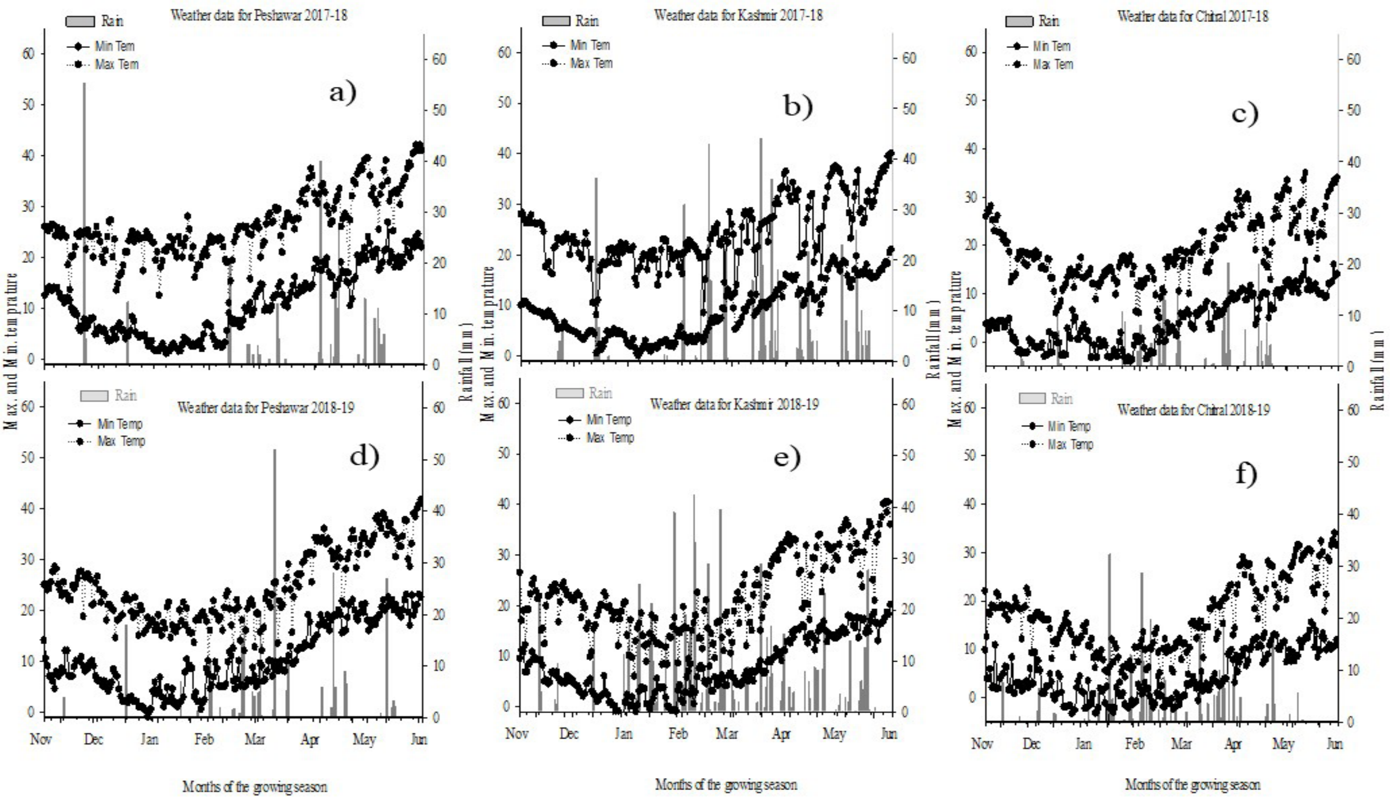

Figure 1: *Temperature (Min. & Max. in ^{O}C) and rainfall (mm) of the seasons 2017-18 (upper windows) and 2018-19 (lower windows) for agro-environment (AEP), (AEK) and (AEC) respectively.*

plowed with a cultivator. On the day of sowing, fertilizers were applied at the rate of 120 (N), 80 ($P\text{-}2O_5$) and 50 (K_2O) kg ha^{-1} respectively from urea, SSP and MOP sources. However, N was applied in two splits one half at sowing and the other half about 50 days after the sowing (DAS) as recommended for the wheat crop.

Experiment details

All agronomic practices recommended for the wheat crop were carried out uniformly for all three AE (*i.e.* locations). However, the AEK was rainfed with no irrigation facility. Harvesting was done on the crop physiological maturity in each AE when a genotype was ready to harvest *i.e.* May 4, 2018 (cv. Pirsabak-2005, Pakhtunkhwa-2015, Pakistan-2013, DN-84 & P-12), May 10, 2018 and 13 2019 (cv. P-2 & P-18) at the AEP, May 25, 2018, and May 29, 2019 in AEK, and likewise on July 10, 2018, and July 15, 2019, in AEC. It is clear that the crop harvesting in AEK and AEC was made on same dates for all 7 genotypes.

Sampling and measurements

Days to emergence, heading, anthesis and maturity were observed by counting the number of days from sowing to the respective growth stage of the crop genotypes within an AE. A meter square sample was marked in an experimental unit and all data were manually recorded during the regular field visits. Tiller's height was recorded by randomly measuring 10 representative samples in an experimental unit from base to tip of the tiller including spikes close to harvesting of the crop. Spike length (cm) was also recorded on the same tillers selected for the tiller's height. Spike weight (g) was recorded on same spikes after drying (70^{O}C) for a week in forced air circulating dryers. Thousand

Table 2: *Days to emergence and heading of wheat cultivars planted in different agro- environments.*

Agro environment (AE)	Days to emergence			Days to heading		
	2017-18	2018-19	Mean	2017-18	2018-19	Mean
AEP	15.3	11.2	13.3 b	107.5	112.7	110.1 c
AEK	15.4	12.1	13.8 b	117.5	119.7	118.6 b
AEC	14.9	14.7	14.8 a	155.5	158.0	156.7 a
LSD (0.05) for AE	0.25	1.51	0.68	1.1	0.7	0.59
Genotypes (G)						
Pirsabak-2005	15.6	12.6	14.1	124.9	127.1	126.0 c
Pakhtunkhwa-2015	15.1	13.2	14.2	129.7	132.1	130.9 b
Pakistan-2013	14.9	12.4	13.7	123.8	127.1	125.4 c
DN-84	14.8	12.6	13.7	121.7	124.7	123.2 d
P-2	15.2	12.2	13.7	131.8	136.6	134.2 a
P-12	15.3	12.4	13.9	124.3	127.0	125.7 c
P-18	15.6	13.2	14.4	131.7	136.3	134.0 a
LSD (0.05) for G	NS	NS	NS	1.3	0.9	0.77
Year mean	15.2	12.7	**	126.8 b	130.1 a	**
Level of significance ($p<0.05$) for treatment interaction						
Y x AE	-	-	***	-	-	-
Y x G	-	-	NS	-	-	-
AE x G	NS	NS	NS	**	**	-
Y x AE x G	-	-	NS	-	-	-

*Means followed by different letters within a category are statistically different using the least significant difference test (p<0.05); * and ** represents the significance at (p<0.05) and (p<0.01); NS =Non-significant*

grains weight (g) was taken on random selected grains samples from seed at harvest, counted 1000 on an auto-counter, dried in forced circulating air dryers for a week and weighed. Grain and biomass yield were recorded by harvesting 4 central rows in an experimental unit, bundled and initially sun-dried for two weeks in field. Each bundle was weighed and separately threshed on a mini-lab thresher. Grains after threshing were collected in paper bags and weighed. Sub samples of both biomass and grains were collected, oven dried for a constant weight and adjusted both biomass and grain yield with expressing in kg ha^{-1}. Harvest index (HI) is expressed in percent as the ratio of the grain to total above ground biomass.

Heat use efficiency (HUE) was derived as a secondary parameter. It is the ratio of the grain yield per unit area (g m^2) obtained from total thermal hours (^{O}C) consumed by the crop in an AE from emergence to physiological maturity for completion of the life cycle. Thermal hours were estimated as the average daily temperature by use of the maximum and minimum in an AE for the crop life cycle.

Data collected during the study were statistically analyzed using the computer software (Statistics) as per procedure explained by Fishers Analysis of Variance Technique using appropriate for the Randomized Complete Block Design (RCBD). Means found significant ($p<0.05$) were separated using the least significant difference (LSD) (Steel *et al*., 1997).

Results and Discussion

Crop developmental stages

Days to emergence, heading (Table 2), anthesis, and maturity (Table 3) of the wheat crop showed significant differences for the treatments Agro-environments (AE) and selected genotypes (G). While averaged across G, significant ($p<0.05$) changes were observed in the crop developmental stages for three AE with no change between AEP and AEK on emergence but with statistical differences for rest of the three developmental stages (*i.e.* heading, anthesis and maturity) for three AE. Emergence is a short-duration stage of the crop and changes in emergence with a reduction of solar radiations expressed significant changes. The genotypes did not differ ($p<0.05$)

Table 3: *Days to anthesis and maturity of wheat cultivars planted in different agro- environments.*

Agro environment (AE)	Days to anthesis			Days to maturity		
	2017-18	2018-19	Mean	2017-18	2018-19	Mean
AEP	116.4	122.6	119.5 c	149	158.7	153.9 c
AEK	125.8	129.4	127.6 b	157.7	163	160.4 b
AEC	180	183.6	181.8 a	227.3	238.7	233.0 a
LSD (0.05) for AE	2.04	1.06	1.02	0.47	1.37	0.65
Genotypes (G)						
Pirsabak-2005	137.9	141.3	139.6 c	174.1	182.4	178.3 c
Pakhtunkhwa-2015	142.2	145.4	143.8 b	179.2	187.3	183.3 b
Pakistan-2013	137.9	142.4	140.2 c	174.7	183.1	178.9 c
DN-84	135.6	140	137.8 d	173.1	180.8	176.9 d
P-2	147.3	153.3	150.3 a	185.1	196.6	190.8 a
P-12	137.4	141.7	139.6 c	174.1	182.0	178.1 c
P-18	146.9	152.2	149.6 a	185.7	195.3	190.5 a
LSD (0.05) for G	1.07	1.24	0.81	1.05	1.42	0.87
Year (Y) mean	140.7 b	145.2 a	**	178.0 b	186.8 a	**
Level of significance (p<0.05) for treatment interaction						
Y x AE	-	-	*	-	-	**
Y x G	-	-	*	-	-	**
AE x G	**	**	**	**	**	**
Y x AE x G	-	-	**	-	-	*

*Means followed by different letters within a category are statistically different using the least significant difference test (p<0.05); * and ** represents the significance at (p<0.05) and (p<0.01) ; NS =Non-significant*

in days to emergence for AEP and AEK but differed ($p<0.05$) for AEC due to cooler climate for more days to complete. Responses of the crop developmental (*i.e.* emergence, heading, anthesis and maturity) confirmed climate effects for the duration within years. Overall growth and development of the crop expressed maximum days to heading, anthesis and maturity in AEC, followed by AEK, and the minimum in AEP, which have confirmed more days in a cooler climate due to higher altitude by extending crop life cycle (Shah *et al*., 2021). Emergence is concerned with soil temperature and moisture. Genotypes may differ but not too much. However, temperatures do play role in open fields making differences for AE (*e.g.* AEC). Differences in AE made seeds to take maximum days into germination in a cooler environment due to higher altitudes. Literature has also confirmed +5 days change in wheat germination for season or delay in sowing (Meleha *et al*., 2020). Days to heading, anthesis and maturity are developmental stages of a crop, which varied for the environment due to location and altitudes. Different days were observed for the same crop for changes in thermal hours (Ahmed *et al*., 2016). All developmental stages of the crop i.e. heading, anthesis and maturity expressed a common trend for an environent by an increase in the altitude (*i.e.* AEP, followed by AEK and AEC), which increased for the decreasing intensity of thermal units (Hatfield and Prueger, 2015). It was has been observed that wheat from emergence to stem elongation faced dormancy due to a decrease in temperature of following days. Growth slows down and stops at temperature (6^{O}C) in winter (Saatkamp *et al*., 2019). The crop is dormant (Renzi *et al*., 2020). Climates of AE differ from mild to marked hence their effect responded accordingly ($p<0.05$) (Rezazadeh *et al*., 2018). Crop, when turns from vegetative to the reproductive stage, has to meet minimum thermal units. Chitral is relatively cool due to the higher altitude. Crop generally expressed late anthesis and maturity with a long dormant phase (Ahmed *et al*., 2016).

Averaged on AE, genotypes differed in day to emergence, heading, anthesis and maturity. Two advanced lines took maximum days. Line P-12 was within ranges with other 4 genotypes expressing the crop developmental phenology. All genotypes, but two lines, differed from each other with smaller variations (p<0.05) for days to heading, anthesis and maturity. The maximum days were taken by lines P-2 and P-18, which confirmed a relatively longer growth vegetative phase (Maeoka *et al*., 2020). Differences in days to heading of genotypes have expressed changes in the active growth period which delayed maturity by confirming the longer life cycle in AEC due to prolonged dormancy (Aslam *et al*., 2017). Differences in genotypes are common but for few days., The more days for an event delayed both anthesis and maturity (Hatfield and Prueger, 2015). Changes heading, anthesis and maturity enable genotypes to recommend for timely sowing where the crop faced an adverse effect *e.g.* heat shock at critical stages, i.e. drought stress, or other weather conditions (Ghosh *et al*., 2020). Two advanced lines (*i.e.* P-2 and P-18), were markedly late in expressing the development stages and could be recommended for cultivation to escape the adverse climate of abnormality. However, all genotypes including the one advance line (P-12) have shown an almost same trend to develop in the 3 environments (Flohr *et al*., 2018).

Days to emergence for interaction (year x AE) showed changes (p<0.05), showing marked changes between years for emergence in AEP and AEK, which were almost similar for AEC due to relatively cooler climates and shorter photoperiod. Emergence is time related activity within limited days' and it differs with changes in soil temperature for one to two weeks (Dos-Santos *et al*., 2019). Days to heading, anthesis and maturity differed for interaction year x AE with almost same patterns between years within an AE. Differences were higher in year 2 due to early sowing of the crop. Nonetheless, AE differs markedly in expressing the crop development for AEC as compared to AEP or AEK. The AEK was relatively dry and cool from the AEP. Crop phenological development took same days in AEP and AEK due to drought AEK despite cool climate and no drought in AEP despite warmer days. Crop in AEC took more days due to cooler climate (Sattar *et al*., 2015). Dormancy of the crop development, therefore extended in cooler climate of AEC, which was crop remained dormant from emergence to stem elongation, which delayed both anthesis and maturity (Rademacher, 2015).

Interaction (genotypes x year) differed for days to heading, anthesis and maturity due to variations in accumulated energy in an environment (Delcour *et al*., 2015). Genotypes differed in the developmental stages expressed in an environment (Eller *et al*., 2020). Crop development is a temperature-related parameter and expressed duration accordingly. Differences in mean thermal units' accumulation in an environment determine length of the growth phases to reach anthesis, heading and maturity. Genotypes x AE interaction was different in a similar fashion for days to heading, anthesis and maturity of the genotypes with the maximum in AEC, followed by AEK and the minimum in AEP (Figure 2). Cooler climates by higher altitudes took more days to express the developmental stage of crop, hence more days required to complete the life cycle (Lippmann *et al*., 2019) subject to similar sowing timings (Hyles *et al*., 2020). Literature has confirmed the delay in anthesis in cooler climates due to limited mean thermal units (Dong *et al*., 2019).

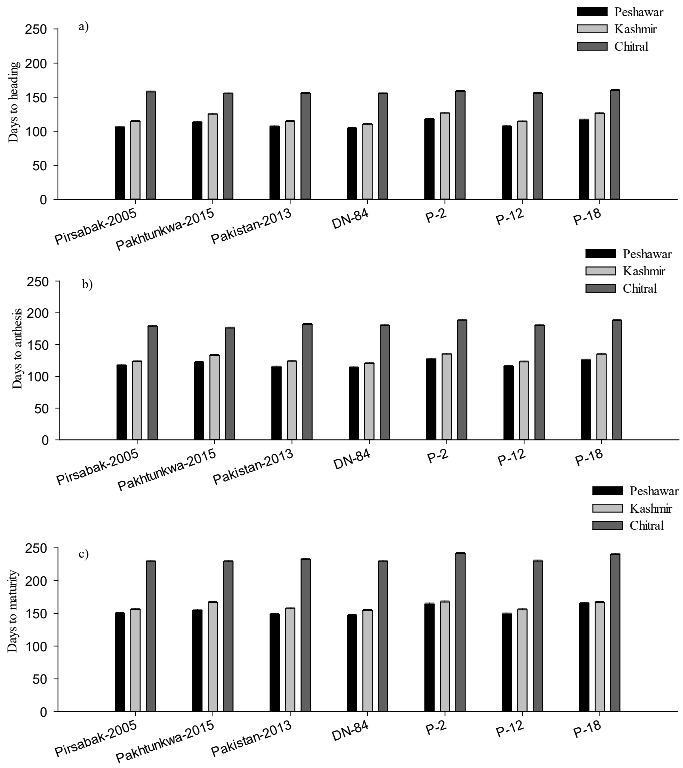

Figure 2: *Treatment interaction (genotypes x AE) in different windows (a) days to heading (b) days to anthesis and (c) days to maturity of wheat genotypes. LSD of mean is shown in vertical bars.*

Treatments interaction (genotypes x year x AE) were significant for days to heading, anthesis and maturity. Wheat took maximum days to heading, anthesis and maturity in AEC followed by AEK and minimum in AEP, which were due to total thermal sunshine hours and their intensity (Yu *et al*., 2018). Cooler climate (AEC) took more days followed by intermediate (AEK) and the lowest by warmers (AEP). However, genotypes differed in AE and years higher readings

Table 4: *Tiller height (cm) and spike length (cm) of wheat cultivars planted in different agro-environments.*

Agro environment (AE)	Tiller height (cm)			Spike length (cm)		
	2017-18	2018-19	Mean	2017-18	2018-19	Mean
AEP	103.4	111.5	107.4 a	9.63	10.32	9.98
AEK	86.1	98.8	92.5 c	9.42	9.8	9.61
AEC	105.1	100.7	102.9 b	10.17	9.9	10.04
LSD (0.05) for AE	8.94	1.96	4.08	NS	NS	NS
Genotypes (G)						
Pirsabak-2005	100.1	99.3	99.7 b	9.29	9.42	9.35 d
Pakhtunkhwa-2015	96.8	101.2	99.0 b	9.70	10.02	9.86 c
Pakistan-2013	97.2	99.5	98.3 b	9.70	10.09	9.89 c
DN-84	90.5	95.3	92.9 c	8.79	9.20	9.00 e
P-2	113.0	117.9	115.5 a	10.79	11.00	10.89 a
P-12	95.9	102.2	99.1 b	9.71	9.84	9.78 c
P-18	93.9	110.2	102.1 b	10.19	10.49	10.34 b
LSD (0.05) for G	10.26	2.24	5.16	0.46	0.23	0.25
Year (Y) mean	98.2 b	103.7 a	**	9.74	10.01	NS
Level of significance (p<0.05) for treatment interaction						
Y x AE	-	-	**	-	-	NS
Y x G	-	-	NS	-	-	NS
AE x G	*	**	**	**	**	**
Y x AE x G	-	-	NS	-	-	NS

*Means followed by different letters within a category are statistically different using the least significant difference test (p<0.05); * and ** represents the significance at (p<0.05) and (p<0.01); NS =Non-significant*

for year 2 due to early sowing but more days in AEC due to cooler climate, followed by AEK and AEP. To change the stage of crop development from heading to anthesis and/or maturity, the temperature is a key factor of the environment (Girousse et al., 2021) AE causing dormancy between the events (Flohr et al., 2018). Nonetheless, responses of genotype in an AE govern by thermal units during growth and genotype to respond (Abdelrahman *et al*., 2020). We have seen almost similar trends in crop developmental stages for genotypes but environment.

Yield contributing traits

Primary yield contributing traits are tillers per unit, grain number and grain weight. Using a similar seed rate with similar tillering potential, the density per unit did not differ (Bastos *et al*., 2020). However, the most interesting was comparing their spike-length and -weight which caused variations in grain number and/or their weight (Arjona *et al*., 2018). Comparing the crop phenology, tillers height (Table 4) differed significantly ($p<0.05$) with the highest in AEP, followed by AEC and lowest in AEK. Tiller height is a genetic character but is strongly influenced in an environment (Duan *et al*., 2020). A warmer climate *e.g*. AEP with sufficient water enables plants to grow faster in daily thermal units' expansion (Clarke *et al*., 2015). Wheat, after emergence, passes the dormancy duration depending on spring starts. Shorter the winter in an environment limited will be dormant period to start vegetative growth also making differences in tiller number and height AE. Literature has also confirmed that tiller height (cm) differed in different environments due to differences in temperatures of the growing days which promote internode length, accordingly (Bilgin *et al*., 2016). The mean daily temperature of the crop growth period is important but drought plays a major role to inhibit stem elongation (Breitkreuz *et al*., 2020). Optimum mean thermal hours of the growth period, when coordinated with drought, has strongly affected stem sizes *e.g*. as observed in AEK (Gleason *et al*., 2017). Genotypes differed in tiller's height with the maximum for P-2, thereafter, rest of the genotypes were statistically the same to each other. However, the lowest tiller height was recorded for DN-84. Tiller height does vary within genotypes, which is mainly due to node number and internode length of the genotype (Liu et al., 2021). The more optimum or close to optimum temperatures for the days results in longer internodes and hence the tiller's height in an environment subject to sufficient soil moisture. Besides the environmental changes, genetics of the genotypes do play a role to express the maximum height in an environment (Mishra *et al*., 2017). Rapid increase in temperature in the following days contributed towards growth with maximum internode length (Steinfort *et al*., 2017). Differences among s environment for trait *i.e.* height AE are obvious to classify them tall and dwarf (Munsif *et al*., 2016).

Interaction (AE x year) showed ($p<0.05$) taller tillers at AEP and AEK but otherwise in the AEC in year 2. Early sowing in year 2 yielded taller plants. However, the longe dormancy of winter with a steady increase in temperature at AEC did not show any change in tillers height. Snowfall in winter increased dormancy after emergence which showed a non-significant effect on tiller height (Bisbis *et al*., 2018). Crop growth from minimum to optimum temperature is static and contributes to a uniform growth in an environment during the season (Anjum *et al*., 2021). Contrary to the AEC, growth in AEP and AEK was subjected to a limited dormancy phase (Munsif *et al*., 2015). Interaction genotypes x AE showed a significant change ($p<0.05$) in height (Figure 3a). Genotypes showed alike trend for the tiller height and varying responses observed for lines. Tiller height of genotypes was lower in AEK due to drought when compared with AEP and AEC. Similarly, the tiller height of Pirsabak-2005 and Pakistan-2013 did not differ in AEP and AEC but was lower in AEK. Pakhtunkhwa-2015 showed taller plants in AEC. Temperature and soil moisture are governing factors of plant growth (Hatfield and Prueger, 2015) and hence the growth was higher in AEP with limited days (Klepeckas *et al*., 2020). Crop in AEP exposed to a relatively higher daily temperature with adequate irrigation hence showed the same height as observed in AEC. Whereas lines showed longer internode length while comparing AEP with AEC and AEK., Plants with longer internodes are the genotype better interaction with the environment (Bhutto *et al*., 2021).

Spike length, spike weight and unit grain weight

Grain yield showed a close association with the spike length (cm), spike weight (g) and grain weight (g) for different ($p<0.05$) environments and genotypes x AE interaction (Table 4 and 5). Two years' data did not show any change ($p<0.05$) in spike length for different environments (Table 4) but did differ for the genotypes. Contrary to this, spike weight was higher in AEC and lower in AEK with no change ($p<0.05$) in AEP. Likewise, 1000 grains weight was observed highest in AEC, followed by AEP and lowest in AEK (Table 5). Spike length depends on spikelet number, which contributed to the spike length. Average over genotypes, spikelets did not differ in number hence the spike length was unchanged within environments (O'Brien *et al*., 2019). Grain size and number differed within spikes for the genotypes, due to the genetic characters. Temperature does play a role within an environment for grain development that makes changes within spike weight for the different environments (Asif *et al*., 2019). Grain assimilates production and partitioning to sink depends on prevailing temperature, which was observed lower in AEC, followed by AEK and AEP. The assimilates production is usually reported higher at cooler climate *e.g.* AEC, which resulted in heavier grain weight (Phung *et al*., 2019). Grain weight in AEK was lowest due to drought which limits grain development despite the favorable climate (Daryanto *et al*., 2017). The more number and weight of grains contributed to heavier spike and finally, the yield *e.g.* in AEC. Spike weight in AEP and AEK was the same but differed in grain weight showing that the drought effect was strong enough to reflect on the sink (Wang *et al*., 2019). Temperatures do play a role in spike weight but drought stress (Javadipour *et al*., 2019). While averaged across AE, genotypes differed significantly in spike length, spike weight and grains weight. Maximum spike length associated with line P-2, followed by P-18. All genotypes including line P-12 reflected a similar spike length except the Pirsabak-2005 and DN-84. Spike weight associated with grain weight, which differed in genotypes. Grain size depends on assimilates accumulation rate during growth which also corresponds to flag leaf area (Kajla *et al*., 2015). Genotypes differ in grain size, hence showed variations in spike weight including grain index (Wang *et al*., 2018b). The spike weight of a genotype depends on spike efficiency from the available sources *i.e.* leaf area and flag leaf to contribute for grains. Spikelets on spike showed grain number and their weight (Steinfort *et al*., 2017). Genotypes differ in sensitivity to carbohydrates supply from sources that adversely affect grain weight (Shi *et al*., 2016). Sensitivity of fertile florets led to increasing abortion in an environment which may lead to differences in spike weight and/or grain number (Zahra *et al*., 2021).

Table 5: *Spike weight (g) spike^{-1} and thousand grains weight (g) of wheat cultivars planted in different Agro-environments.*

Agro environment (AE)	Spike weight (g) spike^{-1}			Thousand grains weight (g)		
	2017-18	2018-19	Mean	2017-18	2018-19	Mean
AEP	2.34	2.72	2.53 b	29.3	32.8	31.0 b
AEK	2.51	2.7	2.61 b	24.1	27.7	25.9 c
AEC	3.2	2.74	2.97 a	48.1	45.4	46.8 a
LSD (0.05) for AE	0.22	NS	0.11	1.4	1.3	0.9
Genotypes (G)						
Pirsabak-2005	2.89	3.00	2.94 a	37.9	38.0	38.0 a
Pakhtunkhwa-2015	2.59	2.79	2.69 b	38.3	37.8	38.1 a
Pakistan-2013	2.81	3.04	2.92 a	37.4	38.5	37.9 a
DN-84	2.61	2.58	2.60 bc	31.3	33.2	32.3 c
P-2	2.71	2.38	2.54 c	28.7	29.1	28.9 e
P-12	2.52	2.63	2.57 bc	35.1	38.8	37.0 b
P-18	2.64	2.62	2.63 bc	28.0	31.6	29.8 d
LSD (0.05) for G	0.17	0.16	0.12	1.1	1.23	0.81
Year (Y) mean	2.68	2.72	NS	33.8 b	35.3 a	***
Level of significance ($p<0.05$) for treatment interaction						
Y x AE	-	-	**	-	-	**
Y x G	-	-	**	-	-	**
AE x G	**	**	**	**	**	**
Y x AE x G	-	-	**	-	-	**

*Means followed by different letters within a category are statistically different using the least significant difference test ($p<0.05$); * and ** represents the significance at ($p<0.05$) and ($p<0.01$); NS =Non-significant*

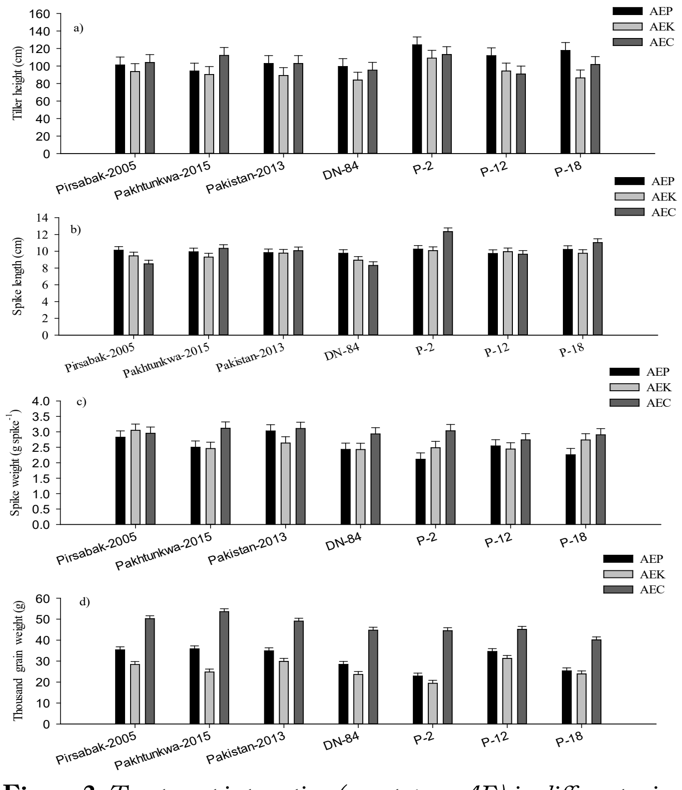

Figure 3: *Treatment interaction (genotypes x AE) in different windows (a) tiller height (b) spike length (c) spike weight and (d) thousand grain weight (g) of wheat genotypes. LSD of means is shown in vertical bars.*

Interaction (AE x year) reflected a higher spike weight in AEP and AEK in year 2. The crop was sown relatively early in season hence, took more days to develop and resulted in healthy spike weight (El-Nakhlawy et al., 2015). Optimum growth conditions contributed to the maximum grain potential and weight (Hazari *et al*., 2019). Both AEP and AEK showed higher grain weight whereas the AEC did not show the same response. In prolonged winter, the slowly rising temperature of spring (*e.g.* AEC) during the growing seasons supported grain development to accumulate better assimilates with heavier spike weight (El-Nakhlawy *et al*., 2015). Interaction (genotypes x year) exhibited marked differences in spike weight in year 2for the maximum genotypes with visible for Pakistan-2013. However, genotypes DN-84 and P-18 did not show a change in grain weight. Spike weight is grain and its biomass, which varied for genotypes (Ding *et al*., 2020). Differences in grain weight of genotypes related to genetic; *i.e.* source capacity for sinks. Smaller grain sizes usually affected less spike weight (Alonso *et al*., 2018). Moreover, changes in flag leaf area also affect grains weight accordingly (Aldesuquy *et* *al*., 2018). Changes in grain weight of genotypes are obvious due to grain sizes (Li *et al*., 2016). Moreover, anthesis timings and conditions also play their role in grain weight of genotype in an environment (Huang *et al*., 2020).

Treatment interaction (genotypes × AE) was significant for spike length with different trends for the genotypes in different environments (Figure 3b). Spike length was relatively higher for Pirsabak-2005 and DN-84 in AEP to AEK and AEC, whereas, remained the same in Pakistan-2013 and P-12, but a lower spike length was observed in AEK than the rest of twoAE for Pakhtunkhwa-2015 and P-18. The difference in spikes length of genotype is obvious due to arrangements of spikelets and intra-spikelets spaces (Guo *et al*., 2018). Temperature is a key factor of crop growth and development, which changed the photoperiod and light intensity in an environment (Rezazadeh *et al*., 2018). Genotypes do respond accordingly for the spike development. Genotypes with no change in spike length can be considered stable for diverse climates. A reduction in spike length with decreasing temperature in coolers climate *e.g*. AEC limits the genotypes' cultivation. Contrary to the spike length, spike weight showed a different trend for treatment's interaction (genotypes × AE) which was due to straw and grain ratio in the spike weight (Russell, 2017). Spike weight of genotypes within 3 environments *i.e*. AEP, AEK and AEC are shown in Figure 3c. Spike weight of Pirsabak-2005 and P-12 was almost similar in 3 AE, but was higher in AEC for Pakhtunkhuwa-2015 and DN-84, and was lower in AEK for Pakistan-2013. Spike weight is the grain weight and straw (Liu *et al*., 2017b). As compared to straw, both grain number and sizes are strongly influenced by temperature and hence the spike weight (Mansouri *et al*., 2018). Genotypes did differ in grain number but were high in their sizes which made significant changes in spike weights. Size and duration of the flag leaf area are critical to contribute in grain number and more significantly in grains weight. Climate changes of an environment did differ and hence their effect on both spike- and grains weight (Gruszka *et al*., 2020). Moreover, changes in moisture at a critical stage *i.e*. grains development, also affected grain size and weight (Escalona *et al*., 2015). Unit grain weight differs in AE for different genotypes (Figure 3d). As explained earlier, all genotypes showed higher grains in AEC due to a suitable climate for grain development. Grain weight in total spike weight is close to 40%. Changes in spike weight in an environment did not match with the grain weight of genotypes. Both water and temperature played a significant role in grain development. Grain growth in cooler climate was more appropriate and hence all genotypes showed better grain weight in the AEC. Contrary to temperature, drought was the most limiting factor (Velu *et al*., 2016). In the most appropriate temperatures in AEK, drought effect was stronger than AEP (Barlow *et al*., 2015). Any of the tested genotypes including lines could not perform better in AEK due to drought (Yadav *et al*., 2020). Genotypes, therefore, showed a decrease in grain weight in the AEK. All factors interaction (genotypes × AE × year) are interesting part of the spike weight and grain weight and have reflected on genotypes accordingly in different environments which were almost the same for both years of the experiments.

Biomass and harvest index

Biomass and harvest indices (HI) showed variations ($p<0.05$) within genotypes and AE (Table 6). Maximum biomass and HI were obtained in AEC, followed by AEP, and minimum in AEK. According to the literature of Campoy *et al*. (2020), delay in sowing from optimum time caused a significant loss in biomass and harvest index, which is mainly due to limited sources for the sink. A rapid increase in the temperatures of the reproductive phase of the crop growth limits growth with smaller grains and hence decreases the harvest index (Mukhtarullah and Akmal, 2016). A decrease in biomass is highly associated with drought than rising temperature caused more reduction in grain and thus the harvest index (Zhang *et al*., 2018). Despite the lower temperature in AEK, lowest biomass from AEP was due to drought stress. Trends of biomass and harvest index were similar but greater in AEC, followed by AEP and lowest in AEK. While average over AE, genotypes' responses were different in biomass and harvest index. Both lines (P-2 and P-18) were tall and hence showed higher biomass., Pakistan-2013 and Pakhtunkhwa-2015 were similar ($p<0.05$) in biomasses due to optimum heights (Awan *et al*., 2017b). Harvest index was high for Pakistan-2013, followed by P-12 and DN-84. The lowest HI was noted for P-2. Changes in biomass are common among genotypes but changes in grain size and weight affect harvest index (Porker *et al*., 2020). Drought and temperatures affected grain size and number which made differences in harvest index (Pradhan *et al*., 2019).

Table 6: *Biomass yield (kg ha^{-1}) and harvest index (%) and of wheat cultivars planted in different Agro-environments.*

Agro environment (AE)	Biomass yield (kg ha^{-1})			Harvest index (%)		
	2017-18	2018-19	Mean	2017-18	2018-19	Mean
AEP	9823	11683	10753 b	29.93	28.67	29.30 b
AEK	7052	7762	7406 c	25.45	27.97	26.71 c
AEC	13507	12480	12993 a	42.24	40.9	41.57 a
LSD (0.05) for AE	543.9	804.4	432.3	1.53	1.9	1.09
Genotypes (G)						
Pirsabak-2005	9684	10295	9990 de	35.76	34.59	35.17 b
Pakhtunkhwa-2015	10501	10579	10540 bc	31.59	31.62	31.61 d
Pakistan-2013	10291	10740	10515 bc	37.02	36.28	36.65 a
DN-84	9275	9942	9609 e	33.5	32.76	33.13 c
P-2	10580	11249	10915 ab	27.02	27.25	27.13 f
P-12	9698	10545	10121cd	34.71	35.58	35.15 b
P-18	10860	11142	11001a	28.2	29.53	28.86 e
LSD (0.05) for G	612.7	665.6	444.6	2.2	1.93	1.44
Year (Y) mean	10127 b	10642 a	**	32.5	32.5	NS
Level of significance (p<0.05) for treatment interaction						
Y x AE	-	-	**	-	-	**
Y x G	-	-	NS	-	-	NS
AE x G	**	**	**	**	**	**
Y x AE x G	-	-	NS	-	-	NS

*Means followed by different letters within a category are statistically different using the least significant difference test ($p<0.05$); * and ** represents the significance at ($p<0.05$) and ($p<0.01$); NS =Non-significant*

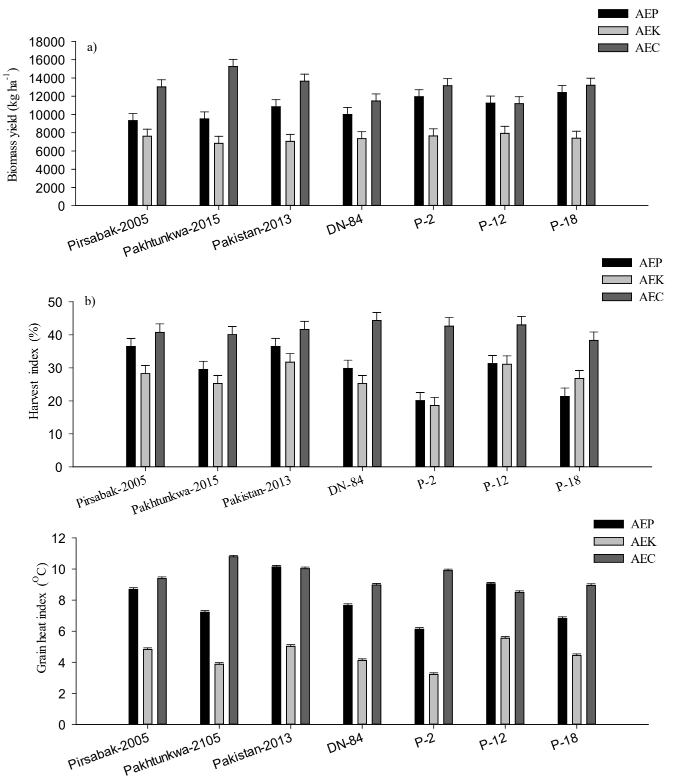

Figure 4: *Treatment interaction (genotypes x AE) in different windows (a) biological yield (kg ha^{-1}),(b) harvest index (%) and (c) grain heat index (°C) of wheat genotypes. LSD of means is shown in vertical bars.*

Interactive effect of treatments (AE x year) showed an increase in biomass in year 2 for AEP and AEK but AEC. The AEC did not differ in sowing dates as well as the crop faced a longer dormancy in winter. Both AEP and AEK biomasses were decreased by delay sowing for a week. The HI in AEP did not differ Temperature, undoubtedly, is the main factor but the drought stress effect cannot be neutralized with temperature (Fahad *et al*., 2017). The wheat harvest index is around 35% Mild temperatures growth in AEC showed a higher harvest index, whereas, growth in high temperature (AEP) and/or drought with low temperature (AEK) the almost same harvest index. Growth is an outcome of climate. Climate of the AEC was stable with slow rise. Whereas, the climate of AEK was mild but faced drought and the climate of AEP was warm but no drought. Effect of low temperature without stress favors growth with better yield (Chen *et al*., 2015). Interaction (genotypes x AE) also expressed variation in biomass and harvest index (Figure 4). Some genotypes express better biomass in an environment. Biomass accumulation per unit area and time expressed yield, which correlated for the growth (Zhang and Flottmann, 2016). Longer days resulted in better growth subject to a stable increase in temperature (Magney *et al*., 2016). It is due to plant accumulate more matter with slow down senescence (Porker *et al*., 2020). A rapid increase in temperature promoted stem elongation and limited leaf area which also adversely affected leaf number and sizes to change biomass and harvest indices accordingly (Schreel *et al*., 2019). Early senescence at high temperature or drought decreased biomass, which also limits grain size and weight and hence harvest index (Pradhan *et al*., 2019). Drought (AEK) as compared to higher temperature (AEP) was observed the same for P-12, P-2, but different for P-18 due to differences in total life cycles and late anthesis. Whereas, rest of the genotypes did not show such a response in harvest index (Akmal *et al*., 2014). Changes in AE for different genotypes are common, but significant variations due to crop morphology and genotypes' interaction with environments is obvious.

Table 7: *Grain heat index (°C) of wheat cultivars planted in different agro-environments.*

Agro environment (AE)	Grain heat index (°C)		Mean
	2017-18	2018-19	
AEP	1.30	1.35	1.33 b
AEK	0.67	0.81	0.74 c
AEC	1.60	1.56	1.58 a
LSD (0.05) for AE	0.08	0.10	0.06
Genotypes (G)			
Pirsabak-2005	1.26	1.29	1.27 bc
Pakhtunkhwa-2015	1.21	1.22	1.22 c
Pakistan-2013	1.40	1.40	1.40 a
DN-84	1.13	1.17	1.15 d
P-2	1.05	1.09	1.07 e
P-12	1.22	1.34	1.28 b
P-18	1.09	1.16	1.12 de
LSD (0.05) for G	0.09	0.08	0.06
Year (Y) mean	1.19	1.24	
Level of significance (p<0.05) for treatment interaction			
Y x AE	*		
Y x G	NS		
AE x G	**		
Y x AE x G	NS		

*Means followed by different letters within a category are statistically different using the least significant difference test (p<0.05); * and ** represents the significant at (p<0.05) and (p<0.01); NS =Non-significant*

Grain heat index (°C)

Grain heat index (GHI), the ratio of grain yield (kg ha^{-1}) to accumulated heat units (°C) in an environment, differed for AE with highest in AEC, followed by AEP and lowest in AEK (Table 7). This pattern was found common for two years. Sunshine duration differed for the environment with location and altitude, which affects both photoperiod and its intensity hence affected days to emergence. Thereafter, the dormancy in winter duration. Total growth durations were reported highest in AEC, followed by AEK and lowest in AEP. The AEK was mild in temperature but drought could not compensate for the growth and hence the yield. Plant biomasses due to climate differs and hence reflected a pattern of highest GHI at AEC, followed by AEP and the lowest at AEK. It is obvious that cooler climates with higher altitudes have lower heat intensity, but drought effects were stronger (Arshad *et al*., 2017) which cannot be compensated with mild days for the crop growth. The GHI was noted lowest in AEK than AEP (Vazquez-Ramirez and Venn, 2021). Altitude is decreased heat intensity, which delays maturity but not under drought (Arshad *et al*., 2017). Right after sowing, a decreasing temperature in the following days and/or winter snow may extend the crop dormancy but thereafter the rising temperature plays a major role in biomass and yield that affects the harvest index (Hoyle *et al*., 2015). Our results also confirmed the lowest GHI in AEK with greater effects on yield by drought besides the relatively low temperature as compared to AEP. The GHI in AEC was the highest due to better yield despite the crop remained dormant for the maximum days (Li *et al*., 2015). Nonetheless, days taken by the crop in AEK were relatively more than AEP but drought effects were not compensated for the crop. Genotypes differ in maturity and for their responses to the climates. The GHI was highest for Pakistan-2013, followed by P-12 and Pirsabak-2005 with the lowest for P-2 due to their life cycles. The GHI of genotypes varied which showed changes in grain yield. The higher GHI of a genotype expressed its suitability for a wider environment. The genotype, with higher GHI, could be ranked suitable for general cultivation in diverse environments. Among treatment interactions (year × AE) and (genotypes × AE), GHI also differed (Figure 4). Crop planted early in year 2 reflected higher yield and hence the GHI Literature has confirmed drought effect stronger than any other factor of production (Daryanto *et al*., 2016). Interaction (AE × genotypes) revealed diversified trends with stability for Pakistan-2013 but in AEK due to drought. Rest of the genotype did not show a comparable response for GHI for environments. Changes in GHI of genotypes limit their wider cultivation when compared with Pakistan-2013.

Conclusions and Recommendations

The study concludes that genotype x environment interaction is an important parameter to identify the scope of the genotype for future food security. The most appropriate genotype has the potential to perform in diversified environments and should be recommended for a profitable crop to ensure the future food security of the growing population. Contrary to this, a genotype with better performance in an environment should be defined with its limitation for the environment and expression of the growth traits not to risk the food security of the growing population and abrupt climate changes in the environment.

Novelty Statement

Focused on the interactive effects of selected high yielding varieties response for changes in different climates.

Author's Contribution

Rabia Goher: Conducted the research, prepared and drafted the manuscript.
Inamullah: Proofread and improving the manuscript.
Mohammad Akmal: Supervised the researcha and proofread the manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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