Research Article

Genotype by Environment Interaction in Bread Wheat Across Dry land Environments

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Abstract | Genotype by environment (GE) interaction complicates selection process of desirable genotypes. Therefore, newly developed germplasm or genotypes needs to be evaluated in multi-environment trials (METs) to know yield potential and adaptability. This experiment was designed to interpret GE interaction using 55 $F_{5:8}$ bread wheat recombinant inbred lines (RILs) with five checks. Experimental material was planted using alpha lattice design in two replicates at Peshawar (E1and E5), Kohat (E2 and E6), Sarai Naurang (E3 and E7) and Dera Ismail Khan (E4 and E8) (Khyber Pakhtunkhwa) during 2014/15 and 2015/16. Locations in each year were considered as independent environments. Pooled ANOVA revealed significant interaction due to GE for days to heading, days to maturity, grain filling duration, grain growth rate, grains spike^{-1}, 1000-grain weight and grain yield. Averaged over eight environments, wheat RIL's 44, 55, and 25 were desirable for days to heading, days to maturity, grain filling duration, grain growth rate, grains spike^{-1} and grain yield. Mean grain yield ranged from 1613 to 2471 kg ha^{-1} across environments. Among the tested environments, Sarai Naurang (E3 and E7) was identified as highly productive environment. The RIL25 had superior performance for various traits. Wheat RIL25 produced maximum grain yield in E2 (3123 kg ha^{-1}), E3 (3665 kg ha^{-1}) and E7 (3256 kg ha^{-1}), thus emerged as promising line with wider adaptation. Conversely, RIL24 had higher grain yield in E1 (2800 kg ha^{-1}); RIL1 in E4 (2884 kg ha^{-1}); RIL58 in E5 (2370 kg ha^{-1}); RIL7 in E6 (3200 kg ha^{-1}) and RIL53 in E8 (2339 kg ha^{-1}) suggesting their specific adaptability to respective environments. Grain yield was significantly correlated with days to heading, grain growth rate and grains spike^{-1}. Keeping in view the significance of GE interaction, it would be worthwhile to carryout stability analysis for identifying high yielding RILs with suitable stability.

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Introduction

Wheat is a leading food crop in Pakistan. It contributes 9.6 percent to the value added in agriculture and 1.9 percent to the GDP of Pakistan. During 2017/18, wheat crop was grown on an average of 8.74 million hectares which produced 26.12 million tons with an average yield of 2.6 tons ha^{-1}. In Khyber Pakhtunkhwa province, it was grown on 0.73 million hectares which produced 1.34 million tons with an average yield of 1.7 tons ha^{-1} (PBS, 2018). The average wheat production in the country, however, is well below than its true potential due to various reasons.

Crop plant is exposed to a range of environmental factors which greatly influence its yield performance. In Khyber Pakhtunkhwa, wheat is mostly planted under rainfed conditions. The situation aggravates by erratic distribution of rainfall which results in poor yield.

Higher dry root weights, longer roots, long coleoptiles and higher root to shoot ratio may results due to drought stress at seedling stage which could be used as selection criteria while breeding for drought resistance (Takele, 2000; Dhanda et al., 2004; Kashiwagi et al., 2004). Forty five percent of the world's geographical area is under drought stress causing major reduction in agriculture productions. Unfortunately, the available wheat germplasm in Khyber Pakhtunkhwa does not possess tolerance to drought stress. Consequently, farmers have to plant low yielding varieties which have not even been bred for water scarce conditions. Therefore, development of such varieties which can effectively withstand drought stress is a viable option to stabilize yield over years. The evaluation of varieties in a series of diverse environments to test consistency in yield is therefore, an integral part of breeding for stress environments.

Genotypes when tested across different environmental conditions often show significant variation in grain yield. This fluctuation is generally known as GE interaction. However, GE interaction is likely to be more severe in stress conditions which complicate the process of selecting high yielding stable genotypes (Cooper and Byth, 1996). Therefore, breeding programs are tended to test extensively newly developed material in diverse environments to increase the chances of success (Alwala et al., 2010). The current study was therefore carried out to test newly developed 55 bread wheat RILs along with five checks at four different locations of KP under rainfed conditions across two years to identify high yielding stable wheat lines.

Materials and Methods

This experiment was designed to determine the GE interaction for grain yield and other production traits in bread wheat. A total of 55 bread wheat RILs and five check cultivars were evaluated across four locations over two years.

Description of experiment

Sixty bread wheat genotypes comprising 55 $F_{5:8}$ bread wheat RILs and five check cultivars (Table A) were planted in 5 × 12 alpha lattice designs in two replicates at Peshawar, Kohat, Sarai Naurang and Dera Ismail (D.I.) Khan of Khyber Pakhtunkhwa province, during 2014/15 and 2015/16. Locations in each year were considered as independent environments. Hereafter, these environments will appear in the text as E1, E2, E3, E4, E5, E6, E7 and E8 (Table B). Each genotype was planted in a plot of six rows with 5 m length having row to row space of 30 cm. All cultural practices were kept uniform.

History of breeding material

Some bread wheat populations were bred in the Department of Plant Breeding and Genetics during 2002/03 (Ahmad and Mohammad, 2005). These populations were advanced in bulk till F_4. Single head selection was carried out based on agronomic fitness and disease resistance in F_5. The selected heads were raised in head-to-row scheme for seed multiplication and disease screening against stripe rust. The tested lines were found segregating for stripe rust resistance. Therefore, 20 resistant heads were hand harvested and planted as head-to-row during 2012/13. Heavy infestation of stripe and leaf rust fungi offered good opportunity for screening $F_{5:7}$ RILs. Fifty-five $F_{5:8}$ RILs were selected based on disease resistance and yield performance for further evaluation in multi-location and multi-year trials under rainfed conditions.

Traits measurement

Days to heading were taken as days from planting to the date when 50 % of the spikes got emerged completely from flag leaf. Days to maturity were counted from the date of planting to the time when more than 80 percent of the plants turned yellow. Grain filling duration was calculated by subtracting days to heading from the days to maturity (Sayre et al., 1997). Grain growth rate was estimated by dividing grain yield plot^{-1} by grain filling duration (Sayre et al., 1997). Grains spike^{-1} were recorded as reported by Sayre et al. (1997). One thousand grains were taken randomly from the bulk grain yield and were weighed using an electronic balance. Grain yield plot^{-1} was recorded after threshing, and then converted to kg ha^{-1}.

Statistical analyses

Analysis of variance: Field-data were collected at proper wheat growth stages. Each location in each year was considered as single environment. Combined data for environments were subjected to pooled analysis of variance using SAS computer software (SAS, 2009). Upon significant GE interaction, separate analysis of variance for each environment was also carried out.

Table A: *List of genotypes with pedigree used in the current study.*

Genotype	Pedigree	Genotype	Pedigree
G1	Ghaznavi × Khatakwal-25-33-12	G31	Tatara × Inqilab-46-26-17
G2	Ghaznavi × Khatakwal-25-33-15	G32	Tatara × Inqilab-07-04-01
G3	Takbir × Inqilab-00-45-01	G33	Tatara × Inqilab-07-04-05
G4	Takbir × Inqilab-00-45-02	G34	Tatara × Inqilab-07-04-06
G5	Takbir × Inqilab-00-45-05	G35	Tatara × Inqilab-07-04-08
G6	Takbir × Inqilab-00-45-09	G36	Tatara × Margala-00-43-01
G7	Takbir × Inqilab-00-45-12	G37	Tatara × Margala-00-43-02
G8	Takbir × Khatakwal-16-03-04	G38	Tatara × Margala-00-43-07
G9	Takbir × Khatakwal-16-03-05	G39	Tatara × Margala-00-43-13
G10	Takbir × Khatakwal-16-03-06	G40	Tatara × Margala-00-43-16
G11	Takbir × Khatakwal-16-03-07	G41	Tatara × Margala-00-43-19
G12	Takbir × Khatakwal-16-03-09	G42	Tatara × Margala-00-43-20
G13	Takbir × Khatakwal-16-03-10	G43	Tatara × Takbir-19-42-04
G14	Takbir × Khatakwal-16-03-13	G44	Tatara × Takbir-19-42-06
G15	Takbir × Khatakwal-16-03-17	G45	Tatara × Takbir-05-09-08
G16	Takbir × Khatakwal-16-03-18	G46	Tatara × Takbir-05-09-10
G17	Tatara × Ghaznavi-10-22-07	G47	Tatara × Takbir-05-09-11
G18	Tatara × Ghaznavi-10-22-12	G48	Tatara × Takbir-05-09-18
G19	Tatara × Ghaznavi-04-31-03	G49	Tatara × Takbir-05-09-12
G20	Tatara × Ghaznavi-04-31-04	G50	Wafaq × Ghaznavi-26-49-02
G21	Tatara × Ghaznavi-04-31-06	G51	Wafaq × Ghaznavi-26-49-07
G22	Tatara × Ghaznavi-04-31-12	G52	Wafaq × Ghaznavi-26-49-10
G23	Tatara × Ghaznavi-04-31-16	G53	Wafaq × Ghaznavi-26-49-12
G24	Tatara × Ghaznavi-30-48-11	G54	Wafaq × Ghaznavi-26-49-14
G25	Tatara × Ghaznavi-30-48-12	G55	Wafaq × Ghaznavi-15-8-14
G28	Tatara × Ghaznavi-30-48-15	G56	Janbaz (Check-I)
G27	Tatara × Ghaznavi-30-48-19	G57	KT-2000 (Check-II)
G28	Tatara × Inqilab-20-18-20	G58	Amin (Check-III)
G29	Tatara × Inqilab-20-18-08	G59	Hasham (Check-IV)
G30	Tatara × Inqilab-46-26-02	G60	Shahkar (Check-V)

Table B: *Description of eight environments used for evaluation of 60 bread wheat genotypes during 2014-16 cropping season.*

Locations	Year	Environments	Average rainfall (mm)	Altitude (m)	Geographical Position	
					Latitude	Longitude
Peshawar	2014/15; 2015/16	E1; E5	326; 385	359	34.01^0 N	71.46^0 E
Kohat	2014/15; 2015/16	E2; E6	421; 245	508	33.58^0 N	71.45^0 E
Sarai Naurang	2014/15; 2015/16	E3; E7	217; 189	304	32.49^0 N	70.46^0 E
Dera Ismail Khan	2014/15; 2015/16	E4; E8	250; 477	175	31.83^0 N	70.91^0 E

Results and Discussion

Pooled analysis of variance across environments revealed significant differences among genotypes for days to heading, days to maturity, grain filling duration, grain growth rate, and grain yield. Interaction due to GE was also significant for all traits except grains spike^{-1} and 1000-grain weight. Detailed description for each trait is given below.

Days to heading

Pooled analysis of variance revealed significant

Table 1: *Mean squares for various traits of bread wheat RILs during 2014/15 and 2015/16.*

Traits	Replication(E)(df=8)	S-Block (Rep*E)(df=64)	Gen (df = 59)	Env (df =7)	Gen × Env (df = 413)
	MS	MS	MS %SS	MS %SS	MS %SS
Days to heading	69.0	9.0	63.52^{**} 5.6	7571.1^{**} 79.9	11.26^{**} 7.0
Days to maturity	39.9	8.3	17.34^{**} 0.5	28589.8^{**} 96.0	9.98^{**} 2.0
Grain filling duration	136.9	18.4	59.6^{**} 4.1	9641.4^{**} 78.3	17.64^{**} 8.5
Grain growth rate	1177.3	88.3	259.4^{**} 7.8	$11974..1^{**}$ 40.7	138.1^{**} 26.3
Grains spke^{-1}	192.4	44.8	90.45^{**} 9.0	879.2^{**} 10.3	48.23^{ns} 33.4
1000 grains weight	226.7	27.5	33.7^{ns} 2.7	6265.8^{**} 60.6	27.18^{ns} 15.5
Grain yield	2868816.3	127867.6	434319.5^{**} 8.3	12569121.8^{**} 28.4	243096.4^{**} 32.4

*** = Significant at 1% probability, respectively.*

Table2: *Meanperformancefordaystoheadingof60wheatgenotypesacrosseightenvironmentsduring2014/15and2015/16.*

Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	125	113	111	102	99	109	104	100	108	G31	126	111	111	103	100	109	104	103	108
G2	125	112	111	104	98	108	102	99	107	G32	120	113	111	101	98	108	102	100	107
G3	128	112	111	109	101	110	104	101	110	G33	115	108	103	100	99	109	102	100	105
G4	127	111	112	108	102	110	105	102	110	G34	115	105	103	100	99	107	102	104	104
G5	131	110	118	110	105	114	109	102	112	G35	115	113	104	100	99	107	101	100	105
G6	131	118	113	112	103	111	108	100	112	G36	124	115	112	103	97	108	103	104	108
G7	131	118	115	108	103	112	108	100	112	G37	123	111	115	105	101	112	109	102	110
G8	129	117	112	104	102	112	108	103	111	G38	123	111	114	102	101	110	107	102	109
G9	129	118	113	104	102	112	106	103	111	G39	125	109	115	105	102	110	105	104	109
G10	124	115	113	103	98	111	106	103	109	G40	125	114	113	105	99	109	105	95	108
G11	126	115	113	105	97	110	107	99	109	G41	125	112	113	103	99	110	105	101	109
G12	126	115	112	106	98	112	107	101	110	G42	127	117	114	111	101	111	108	103	112
G13	125	115	112	108	99	110	106	98	109	G43	126	112	119	110	102	110	106	101	111
G14	126	112	113	107	97	110	106	100	109	G44	121	109	109	106	100	110	106	100	108
G15	123	113	113	107	98	109	104	102	109	G45	125	113	112	105	99	108	103	100	108
G16	127	116	113	106	103	113	108	101	111	G46	126	115	109	103	97	107	101	102	108
G17	122	117	127	104	100	110	104	97	110	G47	123	117	108	108	99	108	104	100	108
G18	128	115	112	104	95	110	105	101	109	G48	120	116	107	107	103	111	106	101	109
G19	126	112	107	106	99	112	107	100	109	G49	118	115	111	111	99	108	104	100	108
G20	126	114	107	104	100	109	103	97	108	G50	117	119	104	104	99	108	102	103	107
G21	122	106	109	102	99	108	101	99	106	G51	115	114	104	100	99	109	102	101	106
G22	124	108	110	106	100	110	103	102	108	G52	115	113	105	102	99	109	102	102	106
G23	121	111	110	103	97	107	98	101	106	G53	119	117	105	102	97	108	101	102	106
G24	126	109	114	104	96	108	102	102	108	G54	117	116	105	102	102	108	101	102	107
G25	126	114	113	109	96	110	105	103	110	G55	116	120	106	104	96	107	100	99	106
G26	126	117	113	106	102	111	106	104	111	G56	128	118	117	104	101	111	106	101	111
G27	125	117	114	108	100	110	106	102	110	G57	130	115	117	110	98	110	102	103	111
G28	126	117	114	106	102	111	107	101	111	G58	131	118	113	111	100	112	108	102	112
G29	129	115	116	111	103	111	107	99	111	G59	121	116	106	104	97	110	106	102	108
G30	124	112	112	105	99	110	105	100	108	G60	127	115	112	106	100	111	108	102	110
Mean	-	-	-	-	-	-	-	-	-	-	124	114	111	105	100	110	105	101	109
Max	-	-	-	-	-	-	-	-	-	-	131	120	127	112	105	114	109	104	112
Min	-	-	-	-	-	-	-	-	-	-	115	105	103	100	95	107	98	95	104
Desirable RIL	-	-	-	-	-	-	-	-	-	-	34	21	34	34	18	23	23	40	34

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

differences among genotypes, environments and GE interaction for days to heading. Overall, genotypes, environments and genotype by environment interaction explained 5.6%, 79.9% and 7.0% of the total variation, respectively. Environmental effect emerged as important source of variation due to its larger contribution (79.9%) in the total sum of squares (Table 1). Averaged over eight environments, days to heading ranged from 104 to 112 days with an average of 109 days, while it ranged from 115 to 131 days in E1; 105 to 120 days in E2; 103 to 127 days in E3; 100 to 112 days in E4; 95 to 105 days in E5; 107 to 114 days in E6; 98 to 109 days in E7 and 98 to 109 in E8 (Table 2). Mean days to heading of 60 genotypes indicated early heading in E4 (100 days), E5 (95 days), E7 (98 days) and E8 (95 days), whereas, delayed heading was observed in E1 (131 days), E2 (120 days) and E3 (127 days). Among the tested genotypes, the RIL34 was noted with early heading, across environments. Similarly, the RIL34 was also early in heading at E1 (115 days), E3 (103 days) and E4 (100 days), thus confirmed as early heading line across eight environments (Table 2).

Early heading plays an important role in grain filling in majority of crops including wheat. Late heading provides lesser time for grain filling which ultimately reflects in lower grain weight (Nasarullah et al., 2017). Mostly, drought and heat stresses occur at the last stages of wheat crop which may adversely affect the genotype performance. Therefore, lines having early heading are desirable in dry lands. The wheat RIL34 was declared as early heading across tested environments, suggesting tolerance to the varying environmental conditions. Rainfall distribution over these environments classified E3, E4, E6 and E7 as drought stressed environments with lower precipitation rate than others. Early heading was observed in E4, E5, E7 and E8, although there was considerable variation in rainfall distribution in these environments. Whereas, delayed heading was observed at E1, E2 and E3. These environments provided with sufficient amount of rainfall as compared to other environments. Good moisture conditions facilitated genotypes with favourable environments and hence they continued their vegetative growth which resulted in delayed heading. Our results are supported by Ijaz et al. (2013) and Ikramullah et al. (2011), who also reported significant GE interaction for days to heading.

Days to maturity

Combined analysis of variance exhibited significant ($p<0.05$) differences among genotypes, environments and GE interaction. Environments captured 96.0% of the total variation, whereas genotypes and GE interaction explained only 0.5% and 2.0% of the total variation, respectively. Larger contribution of environment to the total sum of squares suggested greater diversity of environments for this trait (Table 1). Averaged over eight environments, data for days to maturity ranged from 157 to 162 days, with an average of 158 days across environments. Early maturity was observed in E4 (143 days), E7 (144 days) and E8 (146 days), while late maturity was noticed in E1 (172 days), E2 (184 days) and E3 (166 days). Among the tested wheat RILs, RIL 53 was noted as early maturing across environments (Table 3). Within each environment, mean data for days to maturity ranged from 156 to 172 days with an average of 161 days at E1, 156 to 166 days with an average of 160 days at E3, 143 to 150 days with an average of 147 days at E4. Minimum days to maturity were recorded for RIL28 at E1; RIL48 at E3 and RIL51 at E4 (Table 3).

The yellowness of flag leaf and spikes indicates the physiological maturity in wheat crop (Hanft and Wych, 1982). Adaptation strategies of plants to drought stress include drought escape, drought avoidance and drought tolerance. Among these strategies, escaping drought involves the completion of the life cycle before the onset of the drought period. Therefore, early maturity has been known as a major drought escaping mechanism, particularly at terminal drought stresses (Levitt, 1980; Chaves et al., 2002). Early maturity was observed at E4, E7 and E8, while late maturity was noticed in E1, E2 and E7. Late maturity could have been due to sufficient rainfall and relatively low temperature during the growing season. Water and temperature regulate many of the physiological and biochemical processes within a plant, which in turn control growth and development towards maturity. Early drought and high temperature increase stress on wheat crop, thus enforcing early maturity, while an adequate amount of moisture with optimum temperature promotes growth and development. Among the tested genotypes, the RIL51 and 53 were noted as early maturing across environments, while less number of days to maturity was recorded for RIL28 at E1, RIL 48 at E2 and RIL51 at E4. These lines could be considered as specifically adapted to their respective environments with relatively maximum rainfall distribution. Worland et al. (2004) reported that photosensitivity and vernalization sensitive genes determine the differences in maturity in different crop varieties because genes responsible for earliness are responsive to temperature. The results in the study for days to maturity are in line with the results of Ikramullah et al. (2011) who also reported significant GE interaction for days to maturity in wheat crop.

Table 3: *Mean performance for days to maturity of 60 wheat genotypes across eight environments during 2014/15 and 2015/16.*

Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	160	179	160	147	155	157	151	148	157	G31	163	178	162	147	155	159	151	155	159
G2	167	178	158	147	154	158	148	146	157	G32	160	178	160	147	162	159	151	150	158
G3	165	180	162	148	155	161	144	152	158	G33	161	176	160	145	156	160	149	154	158
G4	167	177	158	148	157	160	151	150	159	G34	158	180	159	145	160	159	149	153	158
G5	168	181	159	149	158	159	153	149	160	G35	160	180	159	144	159	159	152	150	158
G6	171	182	161	148	158	159	153	149	160	G36	157	181	157	145	156	160	149	150	157
G7	172	182	166	150	159	160	156	151	162	G37	156	181	158	147	156	159	151	154	158
G8	165	176	163	145	157	159	154	154	159	G38	158	182	160	149	160	161	152	152	159
G9	162	180	162	146	160	160	152	151	159	G39	160	182	159	148	158	161	151	153	159
G10	159	180	160	147	158	161	152	154	159	G40	157	181	157	145	157	161	149	149	157
G11	166	180	160	148	159	161	151	151	160	G41	158	181	158	146	154	159	149	150	157
G12	163	177	160	146	157	159	154	153	159	G42	156	180	159	149	156	160	150	153	158
G13	159	180	158	147	157	156	152	152	158	G43	161	178	159	149	160	159	151	151	159
G14	159	181	159	149	159	158	152	154	159	G44	159	181	158	146	158	159	152	148	158
G15	157	181	161	148	158	158	150	155	159	G45	160	179	162	150	158	158	149	149	158
G16	161	181	161	148	157	157	153	154	159	G46	161	184	157	144	160	159	152	151	159
G17	164	181	159	147	153	161	152	154	159	G47	161	176	160	147	155	159	153	150	158
G18	163	181	157	147	154	159	151	152	158	G48	157	177	156	148	156	161	152	151	157
G19	162	181	158	149	155	161	151	153	159	G49	157	179	162	150	158	159	152	148	158
G20	163	182	162	150	159	159	150	154	160	G50	159	177	160	144	159	160	152	148	157
G21	159	183	157	148	159	161	149	153	159	G51	160	182	158	143	159	161	152	153	159
G22	161	181	159	149	161	160	151	155	160	G52	161	180	160	147	155	159	151	151	158
G23	160	177	161	147	160	159	150	151	158	G53	156	178	160	148	156	159	150	150	157
G24	159	177	159	148	155	159	149	154	158	G54	162	177	162	146	157	159	150	151	158
G25	157	175	158	149	156	159	149	153	157	G55	160	175	160	146	159	161	151	151	158
G26	158	180	158	148	154	158	152	153	158	G56	161	180	160	150	157	161	155	151	159
G27	158	182	160	148	158	158	149	154	158	G57	160	179	159	147	157	159	154	155	159
G28	156	176	163	149	158	161	154	154	159	G58	162	180	160	150	157	159	153	152	159
G29	161	177	161	149	162	161	152	156	160	G59	165	179	160	146	158	157	154	153	159
G30	164	175	162	148	158	159	152	154	159	G60	157	180	158	147	157	158	154	152	158
Mean	-	-	-	-	-	-	-	-	-	-	161	179	160	147	157	159	151	152	158
Max	-	-	-	-	-	-	-	-	-	-	172	184	166	150	162	161	156	156	162
Min	-	-	-	-	-	-	-	-	-	-	156	175	156	143	153	156	144	146	157
Desirable RIL	-	-	-	-	-	-	-	-	-	-	28	25	48	51	17	13	03	02	53

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

Grain filling duration

Pooled analysis of variance for grain filling duration revealed significant ($p<0.05$) differences among genotypes, environments and GE interaction. The environment contributed 78.3% of the total variation, while the genotype and GE interaction explained 4.1 and 8.5% of the total variation, respectively (Table 1). Significant GE interaction justified individual analysis for each environment. Data for grain filling duration ranged between 46 and 53 days with an average of 50 days across tested environments. Furthermore, grain filling duration ranged from 29 to 45 days in E1; 56 to 73 days in E2; 32 to 57 days in E3; 37 to 49 days in E4; 42 to 64 days in E5; 44 to 54 days in E6; 40 to 52 days in E7 and 42 to 55 days in E8. Maximum grain filling duration was observed for RIL51 in E1; RIL35 in E2; RIL33 in E3; RIL22 in E4; RIL45 in E5; RIL21 in E6; RIL24 in E7 and RIL29 in E8. However, maximum grain filling duration (53 days) was noted for RIL51across environments.

Table 4: *Mean data for grain filling duration of 60 wheat genotypes across eight environments during 2014/15 and 2015/16.*

Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	35	65	49	43	57	48	47	45	49	G31	37	62	51	44	59	49	49	53	51
G2	43	65	47	43	56	50	47	42	49	G32	40	66	49	46	60	51	49	48	51
G3	37	64	51	38	55	51	40	48	48	G33	45	63	57	45	60	51	47	51	52
G4	40	62	46	39	56	49	46	45	48	G34	43	67	56	45	62	52	47	48	53
G5	37	60	42	39	53	45	44	44	46	G35	45	72	56	44	58	52	51	47	53
G6	40	61	48	37	55	49	46	46	48	G36	33	66	45	42	58	51	46	47	49
G7	41	64	51	46	56	48	48	47	50	G37	33	63	43	43	57	47	42	51	47
G8	36	56	51	45	56	47	46	47	48	G38	35	72	46	47	56	50	45	47	50
G9	33	64	49	41	58	48	46	46	48	G39	35	67	45	43	62	50	46	48	50
G10	35	68	47	48	60	50	46	50	51	G40	32	66	45	41	55	51	44	50	48
G11	40	63	48	45	62	51	44	49	50	G41	33	66	46	43	58	50	45	47	49
G12	37	63	48	41	60	47	47	49	49	G42	29	66	45	42	54	48	42	49	47
G13	34	69	46	42	58	46	46	51	49	G43	35	64	40	39	59	49	46	49	48
G14	33	69	46	42	62	48	46	49	49	G44	39	73	50	41	57	49	46	44	50
G15	34	68	48	42	61	48	46	51	50	G45	35	68	50	45	64	50	46	47	51
G16	34	63	48	41	54	44	46	50	48	G46	35	72	48	41	62	52	51	49	51
G17	42	65	32	43	54	51	48	52	48	G47	38	60	52	39	52	51	49	49	49
G18	35	64	45	44	59	49	47	49	49	G48	38	63	50	41	59	49	46	49	49
G19	36	70	51	43	57	49	44	50	50	G49	39	71	51	40	58	51	49	46	51
G20	37	68	55	46	59	50	47	52	52	G50	43	68	56	40	61	52	50	44	52
G21	37	71	48	48	61	54	48	51	52	G51	45	72	55	43	58	51	50	50	53
G22	37	67	50	49	62	50	49	51	52	G52	45	72	55	45	61	50	49	48	53
G23	39	66	52	47	63	53	52	46	52	G53	38	67	55	46	59	51	49	47	52
G24	34	67	45	48	60	51	47	49	50	G54	45	67	57	44	56	51	49	46	52
G25	32	59	45	39	60	48	45	47	47	G55	44	64	55	42	57	53	51	49	52
G26	32	67	46	48	52	47	47	48	48	G56	34	64	43	46	60	50	49	48	49
G27	33	70	46	44	58	48	43	50	49	G57	30	58	42	37	55	49	52	48	46
G28	30	67	49	44	56	50	48	49	49	G58	31	63	47	39	63	47	45	46	48
G29	33	68	45	40	59	49	46	55	49	G59	44	61	54	43	57	48	48	48	50
G30	40	66	51	45	60	49	48	52	51	G60	31	65	46	41	42	47	46	49	46
Mean	-	-	-	-	-	-	-	-	-	-	37	66	49	43	58	49	47	48	50
Max	-	-	-	-	-	-	-	-	-	-	45	73	57	49	64	54	52	55	53
Min	-	-	-	-	-	-	-	-	-	-	29	56	32	37	42	44	40	42	46
Desirable RIL	-	-	-	-	-	-	-	-	-	-	51	35	33	22	45	21	24	29	51

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

Based on these results, E2, E3 and E5 were identified as productive environments where the tested wheat RILs took maximum days for grain filling (Table 4).

Drought stress usually shrinks the grain filling period, resulting significant reduction in number of days to maturity. This could force genotypes to exhibit their differences (Kilic and Yagbasanlar, 2010). Shortening of grain filling period may result in underdeveloped, small and shrivelled kernels as a result seed weight is radically reduced with a subsequent yield penalty. Ali (2011) reported that wheat grain growth is reduced due to various factors including degree of water deficiency and stress development rate, therefore limit final grain yield. Grain yield is considerably reduced by drought stress during grain filling period (Talebi et al., 2009). All the tested environments were different for rainfall distribution during wheat growing season. Variation in metrological conditions might have caused differences in grain filling duration for the tested genotypes. Among environments, E2, E3 and E5 were declared as productive environments, in which the tested wheat RILs took maximum days for filling the grain. These environments were reported with almost high rate of precipitation, facilitating wheat plants to increase number of days to mature. Elhani et al. (2007) also reported significant GE interaction for grain filling duration in bread wheat.

Grain growth rate

Mean squares for grain growth day^{-1} exhibited significant ($p<0.05$) variations among genotypes, environments and GE interaction. Genotypes, environments and GE interaction explained 7.8%, 40.7% and 26.3% of the total variation, respectively (Table 1). Averaged over eight environments, grain growth rate ranged from 31 to 50 g with an average of 40 g growth day^{-1} (Table 5). At each environment, grain growth rate ranged from 33 to 75 g in E1; 18 to 42 g in E2; 24 to 75 g in E3; 22 to 73 g in E4; 16 to 42 g in E5; 19 to 61 g in E6; 20 to 66 g in E7 and 15 to 45 g in E8. Maximum grain growth rate day^{-1} was recorded for wheat RIL24 in E1; RIL36 in E2; RIL17 in E3; RIL53 in E4; RIL19 in E5; RIL7 in E6; RIL25 in E7 and RIL53 in E8 (Table 5). Overall, RIL53 was noticed with maximum (50 g) grain growth rate across environments. Similarly, RIL53 developed grains with maximum rate in E4 (73 g) and E8 (45 g). Environments E1, E3, E4 and E7 had maximum grain growth rate day^{-1}.

Akram (2011) reported in his study that perhaps less effect of water deficiency may occur during early processes of grain growth. Therefore, a reduction in grain weight and grain yield under post-anthesis water deficiency might reflect the lack of supply of photo-assimilates for grain filling (Ahmadi et al., 2009; Abdoli and Saeidi, 2012). In the present study, significant variation among genotypes and GE interaction for grain growth rate suggested that ranking of genotypes for grain growth was inconsistent across environments. Biologically, this may occur when the contribution (or level of expression) of the genes regulating a specific trait differs among environments (Basford and Cooper, 1998). Rainfall data across environments varied significantly, which might have differentiated genotypes for grain growth rate across environments. Hence, the data may be analysed further through AMMI or GGE biplot analysis to visualize stable genotypes and to understand the contribution of genotypes and GE interaction to the total variation for the trait. Among environments, E2, E3, E4 and E7 were noted with maximum grain growth rate day^{-1}. These environments were recorded with adequate rain showers which thus provided suitable growth conditions to the tested genotypes. Mehari et al. (2015) also found different response of genotypes for grain growth rate day^{-1} across environments in wheat which support the findings of the current study.

Grains spike^{-1}

Mean squares were significantly ($p<0.05$) different for genotypes and environments, however, the GE interaction was non-significant. Overall, genotypes, environments and GE interaction contributed 9.0%, 10.3% and 33.4% to the total sum of squares, respectively (Table 1). Grains spike^{-1} ranged from 43 to 53 grains with an average of 49 grains spike^{-1} across environments. Among environments, grains spike^{-1} ranged from 34 to 66 grains in E1; 39 to 56 grains in E2; 40 to 66 grains in E3; 36 to 66 grains in E4; 42 to 63 grains in E5; 38 to 62 grains in E6; 38 to 63 grains in E7 and 32 to 46 grains in E8. Maximum grains spike^{-1} were produced by RIL43 in E1; RIL25 at E2; RIL30 at E3; RIL26 in E4; RIL24 in E5; RIL33 in E6; RIL25 in E7 and RIL30 in E8. The RIL25 consistently produced maximum grains spike^{-1} across environments (Table 6).

Grains spike^{-1} is another important grain yield component. It has generally been observed that high yield in bread wheat varieties is associated with the increasing number of grains spike^{-1}. Reduced number of grains per spike in water stress conditions affected grain growth stages including embryogenesis and development of kernels (Riaz and Chowdhry, 2003). Many researchers cited that water stress during anthesis stage reduced pollination. Consequently, fewer grains were formed spike^{-1} which resulted in significant loss of grain yield (Akram, 2011). Low yield in water stress condition is also attributable to decrease in fertile spikes and number of grains per spike (Sterling and Nass, 1981). The tested wheat genotypes were significantly different for grains spike^{-1} with non-significant GE interaction, indicating variation among genotypes with no effect of drought. Maximum grains spike^{-1} were produced by RIL43 in

Table 5: *Mean data for grain growth rate (g day^{-1}) of 60 wheat genotypes across eight environments during 2014/15 and 2015/16.*

Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	55	29	43	52	40	48	26	28	40	G31	50	32	49	40	29	49	58	19	41
G2	44	35	53	47	34	50	38	23	41	G32	45	32	46	54	25	51	51	25	41
G3	36	20	31	35	24	51	54	16	33	G33	35	32	34	50	23	51	32	22	35
G4	48	31	45	51	35	49	43	23	41	G34	40	32	31	40	28	52	26	20	34
G5	42	28	56	49	33	45	52	20	41	G35	45	31	35	56	31	52	35	36	40
G6	44	23	43	43	25	49	35	18	35	G36	48	42	56	68	27	51	39	36	46
G7	40	20	32	62	16	48	32	22	34	G37	65	34	62	49	33	47	48	22	45
G8	48	37	35	69	27	47	46	26	42	G38	57	31	51	50	30	50	50	28	43
G9	53	29	28	72	31	48	27	28	40	G39	73	28	47	36	30	50	43	28	42
G10	52	22	33	40	31	50	35	23	36	G40	69	33	55	49	35	51	46	26	46
G11	39	21	28	45	25	51	35	16	33	G41	61	33	59	31	36	50	36	24	41
G12	37	29	51	70	27	47	40	25	41	G42	74	30	52	31	36	48	44	22	42
G13	55	24	48	50	34	46	49	20	41	G43	62	34	66	45	34	49	65	24	47
G14	58	18	27	47	26	48	33	22	35	G44	54	32	41	49	39	49	52	36	44
G15	53	24	31	49	29	48	41	16	36	G45	52	29	45	50	24	50	49	29	41
G16	46	21	34	33	32	44	30	22	33	G46	41	31	57	49	24	52	51	19	41
G17	62	27	75	44	37	51	41	22	45	G47	45	35	42	53	29	51	38	28	40
G18	60	27	40	45	36	49	37	18	39	G48	46	35	52	51	30	49	44	26	42
G19	53	28	53	35	42	49	45	16	40	G49	57	29	54	39	34	51	56	26	43
G20	55	18	42	23	32	50	43	18	35	G50	43	29	36	39	29	52	54	26	39
G21	50	27	35	28	38	54	43	17	37	G51	44	32	45	68	30	51	52	28	44
G22	54	31	44	54	29	50	39	25	41	G52	47	32	33	65	31	50	38	35	41
G23	63	29	35	45	36	53	20	33	39	G53	64	40	47	73	35	51	41	45	50
G24	75	28	45	44	42	51	34	24	43	G54	33	22	24	36	20	51	42	19	31
G25	75	39	53	42	42	48	66	15	48	G55	48	27	28	39	30	53	26	23	34
G26	67	23	51	22	34	47	34	17	37	G56	63	31	48	48	21	50	35	24	40
G27	64	19	56	60	34	48	43	22	43	G57	63	30	50	42	30	49	46	20	41
G28	59	19	40	31	27	50	44	16	36	G58	58	33	50	37	26	47	65	25	43
G29	51	20	47	33	27	49	46	19	37	G59	33	27	37	32	23	48	56	20	35
G30	54	24	41	41	31	49	55	21	40	G60	49	34	56	52	37	47	53	26	44
Mean	-	-	-	-	-	-	-	-	-	-	53	29	44	46	31	49	43	24	40
Max	-	-	-	-	-	-	-	-	-	-	75	42	75	73	42	54	66	45	50
Min	-	-	-	-	-	-	-	-	-	-	33	18	24	22	16	44	20	15	31
Desirable RIL	-	-	-	-	-	-	-	-	-	-	24	36	17	53	19	07	25	53	53

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

E1; RIL37 in E2; RIL43 in E3; RIL26 in E4; RIL24 in E5; RIL33 in E6; RIL25 in E7 and RIL30 in E8. These inbred lines might have drought resistant genes which enabled them to perform better. Among the tested wheat material, the RIL25 was noted with maximum grains spike^{-1} across environments.

1000-grain weight

Combined analysis of variance revealed non-significant ($p>0.05$) differences among genotypes and GE interactions (Table 1). Based on average, 1000-grain weight ranged from 24 to 40 g in E1; 20 to 32 g in E2; 23 to 46 g in E3; 18 to 36 g in E4; 36 to 61 g in E5; 27 to 42 g in E6; 25 to 41 g in E7 and 30 to 40 g in E8. Among genotypes, RIL32 in E1; RIL36 in E2; RIL13 in E3; RIL13 in E4; RIL31 in E5; RIL2 in E6; RIL37 in E7 and RIL37 in E8 were recorded with maximum 1000-grain weight. Wheat RIL13 produced heaviest

Table 6: *Mean data for grains spike^{-1} of 60 wheat genotypes across eight environments during 2014/15 and 2015/16.*

Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	42	48	46	45	43	52	51	37	46	G31	42	48	46	45	43	52	51	37	46
G2	46	48	48	39	42	45	45	38	44	G32	46	48	48	39	42	45	45	38	44
G3	41	52	51	45	42	42	53	37	45	G33	41	52	51	45	42	42	53	37	45
G4	39	45	40	36	54	38	53	42	43	G34	39	45	40	36	54	38	53	42	43
G5	47	48	58	58	58	47	51	40	51	G35	47	48	58	58	58	47	51	40	51
G6	47	40	51	51	45	46	51	41	47	G36	47	40	51	51	45	46	51	41	47
G7	50	52	50	52	48	49	58	40	50	G37	50	52	50	52	48	49	58	40	50
G8	50	52	54	55	46	48	62	33	50	G38	50	52	54	55	46	48	62	33	50
G9	52	44	49	55	45	47	51	36	47	G39	52	44	49	55	45	47	51	36	47
G10	50	42	50	55	48	58	46	34	48	G40	50	42	50	55	48	58	46	34	48
G11	41	39	42	42	49	48	45	34	43	G41	41	39	42	42	49	48	45	34	43
G12	36	39	51	43	55	57	49	35	46	G42	36	39	51	43	55	57	49	35	46
G13	34	44	51	41	51	60	48	41	46	G43	34	44	51	41	51	60	48	41	46
G14	53	44	56	49	60	58	59	40	52	G44	53	44	56	49	60	58	59	40	52
G15	45	44	63	39	44	52	48	40	47	G45	45	44	63	39	44	52	48	40	47
G16	56	46	50	62	61	53	56	39	53	G46	56	46	50	62	61	53	56	39	53
G17	48	42	58	49	55	52	47	37	49	G47	48	42	58	49	55	52	47	37	49
G18	52	43	48	54	58	56	44	35	49	G48	52	43	48	54	58	56	44	35	49
G19	48	52	47	55	55	52	52	37	50	G49	48	52	47	55	55	52	52	37	50
G20	45	46	48	49	59	52	38	35	47	G50	45	46	48	49	59	52	38	35	47
G21	47	44	49	45	56	49	41	39	46	G51	47	44	49	45	56	49	41	39	46
G22	49	40	53	51	49	53	46	34	47	G52	49	40	53	51	49	53	46	34	47
G23	44	48	48	46	52	49	58	40	48	G53	44	48	48	46	52	49	58	40	48
G24	46	48	47	50	63	49	52	32	48	G54	46	48	47	50	63	49	52	32	48
G25	52	54	50	57	54	55	63	36	53	G55	52	54	50	57	54	55	63	36	53
G26	56	50	51	66	54	45	49	32	50	G56	56	50	51	66	54	45	49	32	50
G27	60	46	54	59	52	54	44	38	51	G57	60	46	54	59	52	54	44	38	51
G28	54	43	47	57	56	53	38	45	49	G58	54	43	47	57	56	53	38	45	49
G29	52	47	63	54	54	50	40	45	51	G59	52	47	63	54	54	50	40	45	51
G30	53	48	64	59	50	51	43	46	52	G60	53	48	64	59	50	51	43	46	52
Mean	-	-	-	-	-	-	-	-	-	-	48	47	52	51	52	51	49	38	49
Max	-	-	-	-	-	-	-	-	-	-	66	56	66	66	63	62	63	46	53
Min	-	-	-	-	-	-	-	-	-	-	34	39	40	36	42	38	38	32	43
Desirable RIL	-	-	-	-	-	-	-	-	-	-	43	25	30	26	24	33	25	30	25

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

grains (40 g) across environments. Similarly, RIL13 was also noted with maximum 1000-grain weight in E3 and E4. Moreover, E3, E5 and E7 were productive environments for 1000-grain weight (Table 7).

Thousand-grain weight is useful index for milling yield (Safdar et al., 2009). Maximum grain weight is the cardinal source of high yield in cereal crops. Large and bold grain produce more weight thus increase over all yield. The non-significant GE interaction results for 1000-grain weight, suggested the consistency in performance of genotypes across tested environments. The stability of the tested bread wheat recombinant inbred lines across environments for this trait may be due to their genetic similarity or due to the similarity in response of genes to varying environments. On average, E3, E5 and E7

Table 7: *Mean data for 1000-grain weight (g) of 60 wheat genotypes across eight environments during 2014/15 and 2015/16.*

Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Genotypes	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	32	28	36	31	43	38	51	30	36	G31	32	23	41	24	61	30	46	32	36
G2	33	25	33	22	47	42	45	36	35	G32	39	23	42	26	53	38	49	33	38
G3	39	23	30	20	41	37	53	35	35	G33	33	24	36	30	49	37	51	34	37
G4	40	23	39	29	42	34	53	34	37	G34	25	32	32	28	58	34	48	32	36
G5	32	20	32	35	46	33	51	35	36	G35	24	25	36	27	49	41	48	35	36
G6	31	22	37	23	43	33	51	33	34	G36	32	32	30	25	50	38	42	33	35
G7	29	21	29	25	41	37	58	33	34	G37	32	26	36	30	54	38	56	40	39
G8	30	21	34	29	47	32	62	33	36	G38	29	23	28	25	50	36	50	34	34
G9	35	29	44	32	54	31	51	35	39	G39	31	24	40	26	55	40	39	35	36
G10	33	24	33	28	48	36	46	34	35	G40	30	20	39	25	36	38	39	32	32
G11	36	25	42	22	56	34	45	32	37	G41	33	26	38	22	51	34	41	33	35
G12	31	27	36	22	59	35	49	33	37	G42	31	22	37	26	50	35	56	32	36
G13	38	21	46	36	57	38	48	33	40	G43	33	24	40	28	41	34	51	35	36
G14	28	25	25	25	52	37	59	35	36	G44	32	29	25	31	40	33	44	33	33
G15	30	23	30	25	42	41	48	38	35	G45	26	25	32	24	57	32	46	34	35
G16	30	22	27	26	48	34	56	38	35	G46	32	26	30	23	59	39	47	34	36
G17	31	21	36	19	42	34	47	36	33	G47	28	25	34	25	49	34	47	34	35
G18	30	24	33	23	41	36	44	31	33	G48	29	24	29	26	47	33	46	37	34
G19	32	28	41	24	40	38	52	33	36	G49	29	22	26	26	43	35	44	36	33
G20	29	30	44	18	49	41	38	32	35	G50	33	26	41	24	51	33	59	36	38
G21	34	25	32	29	48	35	41	33	35	G51	26	25	37	28	51	36	52	36	36
G22	31	30	32	27	50	33	46	34	35	G52	27	28	33	30	50	34	48	34	36
G23	31	29	33	28	47	34	58	35	37	G53	33	28	33	28	54	32	50	35	37
G24	33	27	32	25	45	31	52	35	35	G54	30	26	31	25	49	34	57	34	36
G25	29	28	37	24	47	34	63	34	37	G55	35	20	33	27	41	30	52	31	34
G26	31	24	38	23	50	35	49	33	35	G56	40	22	30	26	41	33	51	36	35
G27	28	22	28	20	43	34	44	36	32	G57	36	24	30	25	46	32	48	37	35
G28	33	22	39	24	55	35	38	35	35	G58	32	21	30	29	44	27	48	32	33
G29	31	26	25	25	56	33	40	34	34	G59	31	26	33	24	41	35	56	36	35
G30	32	31	23	25	51	31	43	32	34	G60	30	28	38	23	43	39	54	31	36
Mean	-	-	-	-	-	-	-	-	-	-	32	25	34	26	48	35	49	34	35
Max	-	-	-	-	-	-	-	-	-	-	40	32	46	36	61	42	63	40	40
Min	-	-	-	-	-	-	-	-	-	-	24	20	23	18	36	27	38	30	32
Desirable RIL	-	-	-	-	-	-	-	-	-	-	32	36	13	13	31	02	37	37	13

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

had maximum 1000-grain weight, hence, were favourable environments for 1000-grain weight. Among these environments, E3 and E5 were recorded with relatively maximum precipitation, while E7 was noted with relatively minimum precipitation and hence were declared as low and high stressed environments, respectively.

Grain yield

Analysis of variance for grain yield revealed significant ($p<0.05$) differences among genotypes, environments and genotype by environment interaction. The GE interaction explained maximum (32.4%) variation for grain yield, whereas genotypes and environments contributed 8.3% and 28.4% to the total variation, respectively (Table 1). Grain yield data across environments ranged from 1613 kg ha^{-1} to 2471 kg ha^{-1} with an average of 2009 kg ha^{-1} (Table 8). Data for grain yield ranged from 967 to 2800 kg ha^{-1} in E1; 1417 to 3123 kg ha^{-1} in E3; 1541

Table 8: *Mean grain yield (kg ha^{-1}) of 60 wheat genotypes across eight environments during 2014/15 and 2015/16.*

Geno-types	E1	E2	E3	E4	E5	E6	E7	E8	Mean	Geno-types	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	2511	2998	2641	2884	1648	2956	1333	1561	2317	G31	1822	2119	2742	2056	1161	2074	3117	1106	2025
G2	2117	2760	3185	2111	1197	1771	1944	1233	2040	G32	1656	2165	2173	2023	1413	1683	2778	1322	1902
G3	1517	1718	2225	1500	1307	2078	2233	961	1692	G33	1550	2075	2120	1744	1515	1906	1611	1244	1721
G4	2122	2420	2745	2878	1516	1498	2189	1278	2081	G34	1900	2205	1932	1889	1591	1891	1389	1017	1727
G5	1911	2219	3005	1656	1323	2798	2494	1056	2058	G35	2011	2404	2132	2228	1449	2061	1956	1872	2014
G6	1511	2028	2818	2000	1411	2349	1739	1072	1866	G36	1722	2993	2819	1834	1398	2300	1972	1833	2109
G7	967	1877	2143	1556	1412	3200	1717	1289	1770	G37	2106	2358	2945	2378	1473	2072	2217	1228	2097
G8	1650	2597	2866	1922	1192	2778	2311	1483	2100	G38	1878	2375	2594	2023	1532	2189	2494	1439	2066
G9	1967	2497	2327	2222	1210	2411	1383	1694	1964	G39	2044	1899	2300	2695	1410	2597	2206	1528	2085
G10	2039	2106	2160	2222	1339	1720	1811	1361	1845	G40	2117	1828	2742	2428	1502	2952	2217	1433	2152
G11	1711	1918	2075	1889	1344	1233	1722	1011	1613	G41	2311	2494	2965	2007	1680	2067	1767	1239	2066
G12	1778	2438	3235	1667	1803	2467	2083	1383	2107	G42	2117	2561	2548	2414	1406	1944	1983	1178	2019
G13	2167	2350	2577	2778	1552	2667	2461	1233	2223	G43	2228	2261	2895	2345	1369	2368	3261	1300	2253
G14	1783	1792	1628	2434	1552	2739	1639	1294	1858	G44	2428	2610	2264	2405	1614	2040	2633	1728	2215
G15	1967	2162	2067	2000	1827	2624	2056	1017	1965	G45	1678	2191	2453	2056	1770	1841	2478	1494	1995
G16	1922	1892	2157	1722	1750	1111	1528	1350	1679	G46	1617	2295	3054	2078	1646	2287	2806	1011	2099
G17	2161	2379	2735	2555	1649	2316	2178	1356	2166	G47	1656	2277	2372	2206	1586	2121	2094	1539	1981
G18	2344	2357	2313	2439	2209	1741	1878	1078	2045	G48	1950	2299	2855	2172	1280	2110	2233	1422	2040
G19	2594	2635	3229	2833	1670	1020	2200	928	2139	G49	2172	2081	3082	2460	1665	1874	3039	1289	2208
G20	1967	1841	2507	2333	1579	2663	2283	1133	2038	G50	1950	2141	2255	2219	1466	1889	2983	1278	2023
G21	2450	2419	2845	2556	1518	1353	2300	1017	2057	G51	1894	1950	2747	2301	1457	2676	2872	1539	2180
G22	1983	2781	2769	2734	1304	2113	2111	1494	2161	G52	2061	2249	2037	2722	1318	2191	2028	1878	2061
G23	2522	2805	2198	2655	1759	1630	1183	1878	2079	G53	2300	2891	2818	2072	1162	1820	2250	2339	2207
G24	2800	2517	3252	2833	1593	1338	1817	1472	2203	G54	1267	1417	1541	2017	1662	1938	2261	956	1632
G25	2744	3123	3665	2389	1800	1939	3256	850	2471	G55	1894	1828	1702	2072	1359	1877	1472	1244	1681
G26	1972	2089	3127	2389	1762	1660	1722	983	1963	G56	1411	2037	2144	2306	1672	2017	1928	1306	1853
G27	2156	2452	2922	2000	1570	2643	2000	1322	2133	G57	1800	2045	2257	2133	1757	1608	2594	1072	1908
G28	1694	1947	2703	2000	1224	2063	2333	961	1866	G58	1811	2006	2634	1754	2370	1763	3261	1239	2105
G29	1789	1996	2643	2089	1252	1202	2333	1300	1826	G59	1461	1950	2239	1822	1222	1901	2928	1072	1824
G30	2072	2290	2687	2389	1179	1401	2889	1339	2031	G60	1461	2118	2877	1556	1467	1899	2706	1394	1935
Mean	-	-	-	-	-	-	-	-	-	-	1953	2259	2561	2201	1514	2057	2211	1315	2009
Max	-	-	-	-	-	-	-	-	-	-	2800	3123	3665	2884	2370	3200	3261	2339	2471
Min	-	-	-	-	-	-	-	-	-	-	967	1417	1541	1500	1161	1020	1183	850	1613
Desirable RIL	-	-	-	-	-	-	-	-	-	-	25	25	25	04	58	07	43	53	25

E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

to 3665 kg ha^{-1} in E3; 1500 to 2884 kg ha^{-1} in E4; 1161 to 2370 kg ha^{-1} in E5; 1020 to 3200 kg ha^{-1} in E6; 1183 to 3261 kg ha^{-1} in E7 and 850 to 2339 kg ha^{-1} in E8. Wheat RILs 24, 25, 25, 1, 7, 58, 43, and 53 produced maximum grain yield in E1 (2800 kg ha^{-1}), E2 (3123 kg ha^{-1}), E3 (3665 kg ha^{-1}), E4 (2884 kg ha^{-1}), E5 (2370 kg ha^{-1}), E6 (3200 kg ha^{-1}), E7 (3261 kg ha^{-1}) and E8 (2339 kg ha^{-1}), respectively (Table 8). Among genotypes, RIL25 was the most productive line for grain yield across environments. Similarly, RIL25 out-yielded its counter mates at E1, E2 and E3. Furthermore, E2, E3, E6 and E7 were the highly productive environments, while E1 and E8 were least productive for grain yield.

Grain yield is one of the key economic factors behind a positive wheat cropping enterprise and is therefore a major target for wheat breeding programs (Wu et al., 2012). In this study, data for grain yield revealed significant differences among genotypes which indicated genetic differences among genotypes for this trait. The significant GE interaction further suggested that the tested environments were not similar. Thus, there is no guarantee that a genotype selected in an environment with high rainfall will produce high yields in environments with low rainfall and vice versa. Therefore, indirect selection in drought environment based on the results of optimum conditions will not be efficient (Sio-Se al., 2006). Differences among environments were due to variation in rainfall distribution across environments during wheat growing season. Based on metrological data, environments E2, E3, E6 and E7 were good for grain yield despite drought stress. This indicated the presence of drought tolerant genes, which might have expressed and resulted in higher grain yield. The results in the study for grain yield are in line with the results of Islam et al. (2015) who also reported significant GE interaction for grain yield in spring wheat.

Table 9: *Phenotypic correlation among yield and yield contributing traits of 60 bread wheat genotypes across eight environments.*

	DM	GFD	GGR	GPS	TGW	GY
DH	-0.26	-0.36	0.39	-0.005	-0.31	0.27**
DM		0.80	-0.43	0.0003	-0.04	-0.07**
GFD			-0.52	-0.05	0.10	-0.18**
GGR				0.12	-0.13	0.72**
GPS					-0.007	0.09**
TGW						-0.25**

*DM=days to maturity, GFD=grain filling duration, GGR=grain growth rate, GPS=grains spike^{-1}, TGW=1000-grain weight, GY=grain yield, ** = Significant at 5% probability.*

Correlation coefficients among yield and yield contributing traits of 60 bread wheat genotypes were also computed over eight environments. Correlation analysis revealed that grain yield was significantly correlated with days to heading (r_g = 0.27**), grain growth rate (r_g = 0.72**) and grains spike^{-1} (r_g = 0.09**). Grain yield was negatively associated with days to maturity, grain filling duration and 1000-grain weight. The association of the mentioned traits with grain yield indicated the importance of these traits in higher grain yield (Table 9). Khan et al. (2018) and Mohsen et al. (2012) also reported significant association of grain yield with grains spike^{-1}.

Table 10: *Mean data of environments across genotypes during 2014/15 and 2015/16.*

Environment	DH	DM	GFD	GGR	GPS	TGW	GY
E1	124	161	37	53	48	32	1953
E2	114	179	66	29	47	25	2259
E3	111	160	49	44	52	34	2201
E4	105	147	43	46	51	26	1514
E5	100	157	58	31	52	48	2057
E6	110	159	49	49	51	35	2211
E7	105	151	47	43	49	49	1315
E8	101	152	48	24	38	34	2009

DM=days to maturity, GFD=grain filling duration, GGR=grain growth rate, GPS=grains spike^{-1}, TGW=1000-grain weight, GY=grain yield, E1=Peshawar 2014/15, E2=Kohat 2014/15, E3=Sarai Naurang 2014/15, E4=D.I. Khan 2014/15, E5=Peshawar 2015/16, E6=Kohat 2015/16, E7=Sarai Naurang 2015/16, E8=D.I Khan 2015/16.

Conclusions and Recommendations

Significant genotype by environment interaction suggested the uncertainty in performance of wheat RILs due to diverse environments. Although, Sarai Naurang (E3) was noted with relatively minimum rainfall distribution followed by Kohat (E2) however, Sarai Naurang (E3, E7) produced relatively maximum grain yield. Among the tested wheat genotypes, the RIL34 had early heading; RILs 51 and 53 were early maturing; RIL34 recorded maximum grain filling duration; the RIL25 produced maximum grains spike^{-1}; RIL53 recorded maximum grain growth rate; RIL13 produced heaviest grains and RIL25 had highest grain yield across environments. The mentioned RILs could serve as useful breeding material to improve various plant attributes. Grain yield had significant association with days to heading, grain growth rate and grains spike^{-1}, while the relationship was significantly negative with days to maturity, grain filling duration and 1000-grain weight. Based on results of this study, wheat RIL25 (derived from Tatara × Ghaznavi) was identified as potential line for its superior grain yield across environments, followed by RIL51 and RIL53 (derived from Wafaq × Ghaznavi). However, the use of advance statistical tools for interpreting GE interaction to establish stability of mentioned lines is recommended to reach more credible conclusions.

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Novelty Statement

This research was designed to interpret Genotype by environment (GE) interaction using 55 F5:8 bread wheat recombinant inbred lines (RILs) with five checks. Newly developed germplasm or genotypes were evaluated in multi-environment trials (METs) in order to identify high yielding lines with specific and wide adaptability.

Author's Contributions

This research article is an integral part of doctoral study of the first author Muhammad Ilyas (MI). MI and Fida Mohammad (FM) formulated the research. MI performed the experiments and wrote the first draft of the manuscript. FM made critical corrections in the first draft. Both authors read and approved the final manuscript.

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