Research Article

Genotype by Environment Interactions of Vegetative Growth Traits of Bread Wheat Genotypes

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Abstract | Determining the amount of genotype by environment interaction (GEI) is an important step in identifying high yielding and stable genotypes for cultivar development. Keeping in view the significance of genotype and environment, a multi environment study was conducted to evaluate the response of genotypes to different cropping systems and environments. The performance of vegetative growth traits of the 40 exotic bread wheat lines was assessed across seven different environments during 2015-16 and 2016-17 growing seasons. The trials were conducted using RCB design at four locations for two years; Research Farm, of the University of Agriculture, Peshawar; Agriculture Research Station, Buner; Agriculture Research Station, Baffa, Mansehra; and Barani Agriculture Research Station, Jarma, Kohat (one year only). Data were recorded on leaf area, plant height, biological yield and straw yield. Highest plant height was recorded for G02, G31 and G11. The exotic lines included in the study generally had more plant height in Peshawar as compared to other locations. The highest maximum mean for leaf area was observed for G17 and CSA while minimum was observed for G03 followed by G33 and G25. Among the seven environments, genotypes on average produced larger flag leaves having maximum leaf area in Peshawar while lowest was observed in Mansehra. For straw yield of the 40 genotypes across seven environments, the highest straw yield of 12547 kg ha^{-1} was produced at Mansehra in 2016-17 and the lowest yield of 2440 kg ha^{-1} was recorded at Buner in 2017-18. Overall, the genotypes included in the study had more biological yield in Mansehra as compared to other locations. Line G06 and G17 produced maximum biological yield. The lines with desirable characteristics can be used in hybridization programs to combine these characteristics in single line, or to transfer them to other high yielding varieties.

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Introduction

Bread wheat (*Triticum aestivum* L.), is one of the most important grain crops used as a staple food in many countries. Currently, wheat is the most widely cultivated (approximately 220 million hectares) and consumed cereal crop. A significant population in many countries is largely dependent on wheat and it fulfills a large part of their nutritional requirements. Globally the consumption and demand of plant materials for use as food, feed and fuel is increasing with the increase in population; furthermore, the use of grain crops for biofuel production has placed an additional pressure on the global grain crops supply

(Edgerton, 2009). Wheat is used for food, animal feed and an industrial raw material (Nhemachena and Kirsten, 2017). Consequently, both grain yield and biomass are important products of wheat crop. In Pakistan and other Asian countries wheat straw is an important source of animal feed, it is used in combination with green fodder as well as separately when green fodder is limited (Kumar *et al*., 2013).

The economic yield of grain crops depends on biological yield, which in turn depends on the crop growth rate and crop growth duration; growth rate is primarily affected by assimilates developed in the process of photosynthesis and on the efficiency with which assimilates are partitioned to different plant organs. The grain yield of a crop is therefore dependent upon different aspects of the developmental morphology mostly affecting the photosynthetic machinery and nutrient absorption mechanisms of the plant (Bueno, 1979). Balanced vegetative and reproductive growth and development are important for both biological and economic yields. Vegetative growth is crucial as photosynthetic machinery (source size and activity) is developed during vegetative phase and it also affects reproductive sink capacity and ultimately the seed yield. Plant height is one of the criteria for vegetative growth. Many wheat improvement programs have focused on plant height regulation for increasing grain yield (Wurschum *et al*., 2015). Flag leaf area is a reliable predictor of amount of assimilates synthesized and thus it is directly linked to crop growth, development and health (Alqudah and Schnurbusch, 2015). Flag leaf photosynthesis serves as the main supply of carbon for grain filling (Bishop and Bugbee, 1998). Flag leaf traits such as length, width and area are reported to be positively and significantly correlated to major yield contributing traits. Wheat genotypes having relatively larger flag leaf size tends to produce more grains spike^{-1} (Zhao *et al*., 2018). Among leaf morphology and its component traits flag leaf area is reportedly the most yield contributing trait, followed by flag leaf width and flag leaf length (Fan *et al*., 2015). Maximizing leaf area results in the increase of photosynthetic rate and could be considered an important trait for improvement of yield in wheat (Driever *et al*., 2014). In countries like Pakistan where yield of majority of crops including wheat is comparatively low, there is a dire need to develop new varieties having better agronomic traits and higher yield.

The performance of a particular variety in the field depends upon the genetics, the environment and the response of the genotype to the environment. The response of each genotype is different in different environments as genes of each genotype interact differently with aerial and below ground environmental factors to translate morphological and physiological aspect of crop growth differently. These variable responses of genotypes to environments are called genotype by environment interaction (GEI). The process of selecting superior lines is complicated by the presence of significant G × E interaction (Sohail *et al*., 2016), as in majority of the cases the phenotype is not the actual expression of the genotype and selection may not be very effective (Bondari, 1999). For effective and precise selection of genotypes; the genotypes are tested in different environments and multiple seasons (Ahmadi *et al*., 2012). Hence development of improved wheat varieties that can perform well in different agro-environmental conditions is one of the most cost effective and powerful approaches to increase crop production (Annicchiarico, 2002).

Knowledge of the magnitude and type of GEI is a pre requisite in any breeding program. Considering the importance of genotype × environment interactions, this multi-environment trial was conducted to understand the response of the genotypes to the diverse cropping systems and complexes of environments. The specific objectives of the study were to:

1. Evaluate the performance of exotic wheat lines across the different environments.
2. Assess G × E interaction of exotic wheat lines for vegetative growth traits.

Materials and Methods

This study was conducted to evaluate genotype × environment interaction and the performance of vegetative growth traits of 35 (Genotype, G1-G35) exotic bread lines and five check cultivars (CSA, Morocco, Atta-Habib, Ghanimat and Siran). The present multi-environment study was conducted at four locations during 2016-17 and three locations during 2017-18 wheat growing seasons of the Khyber Pakhtunkhwa province of Pakistan and the seven combinations of years and locations were considered as seven environments as given below:

Environment	Location	Year
E-01	Research Farm, The University of Agriculture, Peshawar	2016-17
E-02	Agriculture Research Station Baffa, Mansehra	2016-17
E-03	Agriculture Research Station, Amnawar, Buner	2016-17
E-04	Barani Agriculture Research Station, Jarma, Kohat	2016-17
E-05	Research Farm, The University of Agriculture, Peshawar	2017-18
E-06	Agriculture Research Station Baffa, Mansehra	2017-18
E-07	Agriculture Research Station, Amnawar, Buner	2017-18

Design and agronomic practices

This study was performed using RCB design having three replications at all environments except at E-07 where two replications were used due to limited land availability. Each experimental unit had four rows which were two meters long and row to row distance was 0.3 meter and hence the plot size was 2.4 m^2. Ploughing, planking and seed bed preparation was done at proper moisture conditions. The application of recommended fertilizer i.e. 120 kg ha^{-1} nitrogen and 80 kg ha^{-1} phosphorous for wheat crop was achieved by applying full dose of DAP and half dose of urea at the time of sowing, the remaining half dose of urea was applied at the time of second irrigation. For planting the experiment recommended seed rate of 120 kg ha^{-1} was used. The calculated amount of seed for each plot (28.8 g) was uniformly distributed in four furrows and covered immediately. Uniform standard management practices were followed to raise the crop at all experimental sites.

Data were recorded on the following vegetative growth parameters:

Plant height: At physiological maturity, height of randomly selected representative plants from each experimental unit was measured from ground level to the tip of the spike excluding awns.

Flag leaf area: Length and width of randomly selected flag leaves in each experimental unit was measured. The leaf area was calculated using the following formula developed by Bari *et al*. (2010) for accurate estimate of leaf area of wheat.

$$1/LA = 0.001666 + 0.27934/LL - 0.0079/LW + 0.43989/(LL*LW) + 0.01445/(LW^2) + 2.4645/(LL^2)$$

Where;

LA is leaf area, LL is leaf length, and LW is leaf width.

Biological yield: The above ground mass from each plot was harvested separately and weighed after having dried in sun for a week to record biological yield $plot^{-1}$. The following formula was used to calculate biological yield in kg ha^{-1}.

$$\text{Biological yield (kg ha}^{-1}) = 10{,}000 \times \text{biological yield plot}^{-1} / \text{plot size}$$

Straw yield: Straw yield was calculated by subtracting grain yield from biological yield.

Statistical analysis

Analysis of variance: Data from all locations and years were analyzed as combined over the environments. The ANOVA appropriate for randomized complete block design was used for analysis of data to test the significance of genotypes, environments and genotypes × environments interaction. Least Significant Difference (LSD) was calculated to compare the means of lines with means of the check cultivars.

Results and Discussion

Plant height

Analysis of variance combined over years and locations revealed that differences among genotypes and environments were significant at $P \leq 0.001$; interaction between genotypes and environments was also significant at $P \leq 0.001$ for plant height (Table 1). These results show that the observable variation present in plant height of these lines is partly due to the differences in the genetic make-up of the lines, partly due to external factors and also due to the differential response of the genetic material of the different lines to the external environmental factors. Maximum portion of observable variation was due to environmental effect (68.31%), followed by GEI (12.32%) and genotypic effect (6.74%). The plant heights of these genotypes were greatly affected by the changes in below ground and aerial environments.

Table 1: *Analysis of variance combined over 7 environments for biological yield and related traits of 40 genotypes of wheat planted in seven environments (at four locations during 2016-17 and three locations during 2017-18 in Khyber Pakhtunkhwa, Pakistan.*

Trait	SoV§	Environments	Reps (E)	Genotypes	G×E	E. Error
	DF	6	13	39	234	507
Plant Height (cm)	MS	9380**	159	142**	43**	16
	% SS	(68.31)	(2.51)	(6.74)	(12.32)	(10.13)
Flag leaf area (cm^{-2})	MS	2406.61**	139.51	116.71**	35.52**	17.48
	% SS	(38.02)	(4.78)	(11.98)	(21.88)	(23.34)
Straw yield (kg ha^{-1})	MS	9875867801**	63216596	104473330ns	485060600**	556150550
	% SS	(89.09)	(0.57)	(0.94)	(4.38)	(5.02)
Biological Yield (kg ha^{-1})	MS	2967968236**	7294976	5276254*	3424799**	1815886
	% SS	(89.8)	(0.48)	(1.04)	(4.04)	(4.64)

§ "SoV" is source of variation; "Reps (E)" is replications within environments; G×E is genotypes by environments interaction; "E. Error" is experimental error.

Across all the seven environments included in the study, the highest plant height was attained by G11 (109.2 cm) in E-01 while the lowest plant height was observed for G33 (66.4 cm) in E-03 (Table 2). Within environments, plant height of the genotypes ranged from 86.9 to 109.2 cm in E-01; 87 to 97 cm in E-02; 66.4 to 84.9 cm in E-03; 70 to 85.7 cm in E-04; 86.4 to 105.4 cm in E-05; 73.7 to 95.6 cm in E-06 and 71.5 to 86.7 cm in E-07. Mean plant height was 98.4 cm in E-01, 92.8 cm in E-02, 76.5 cm in E-03, 79.1 cm in E-04, 96.4 cm in E-05, 82.9 cm in E-06 and 80.4 cm in E-07. Mean values for plant height averaged over all locations and years ranged from 81.3 cm to 91 cm with a grand mean value of 86.9 cm. G11 exhibited maximum plant height of 91.0 cm averaged over all environments, followed by G31 (90.5 cm) and G02 (90.4 cm): G01 had minimum plant height of 81.3 cm; second and third plant height from bottom were recorded for G25 (81.8 cm) and G21 (82.1 cm).

Overall the genotypes included in the study had more plant height in Peshawar (E-01 and E-05) as compared to other locations (Figure 1).

Flag leaf area

Highly significant differences were observed among the genotypes across the seven environments for flag leaf area. The main effect of environments as well as GEI were significant for flag leaf area (Table 1). The phenotypic variation present in the leaf area of the genotypes was influenced by genetic makeup, environment and the interaction between both; genotypes accounted for 11.98% of the variation and GEI accounted for 21.88% of the variation in the leaf area. Maximum variation in the trait was attributed to the environments (38.02%). This signifies that environmental changes had a dominant role and significantly affected the leaf area of the genotypes in this study.

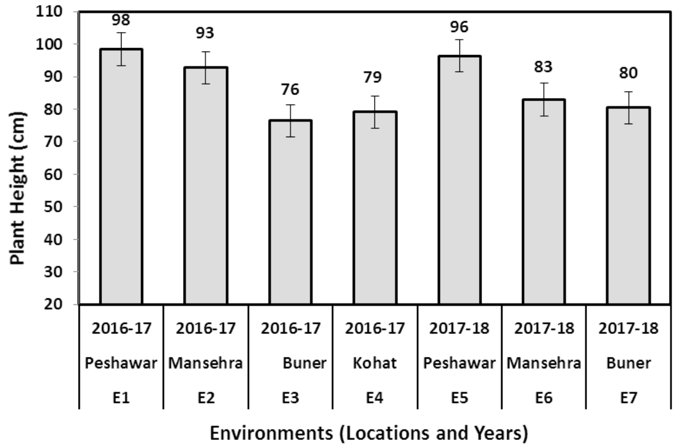

Figure 1: *Plant height averaged over 40 genotypes of wheat, in trials conducted in seven environments of Khyber Pakhtunkhwa, Pakistan during the crop growing seasons of 2016-17 and 2017-18. Error bars are for 1% LSD (5 cm).*

Flag leaf area based on the average of each genotypes in the seven environments ranged from 16.7 cm^2 for G03 at Buner in 2016-17 designated as E-03 to 50.7 cm^2 for CSA at Peshawar in 2016-17 designated as E-01 (Table 3). Within environments, flag leaf area ranged from 28.2 cm^2 to 50.7 cm^2 in E-01; 20.5 cm^2 to 36.0 cm^2 in E-02; 16.7 cm^2 to 32.8 cm^2 in E-03; 20.5 cm^2 to 43.4 cm^2 in E-04; 19.8 to 32.6 cm^2 in E-05; 23.0 cm^2 to 40.5 cm^2 in E-06 and 22.2 cm^2 to 32.4 cm^2 in E-07. Maximum flag leaf area was observed for CSA in E-01 (50.7 cm^2), G02 in E-02 (36.0 cm^2), G10 in E-03 (32.8 cm^2), G01 in E-04 (43.4 cm^2), G02 in E-05 (32.6 cm^2), G15 in E-06 (40.5 cm^2) and CSA in E-07 (32.4 cm^2). Leaf area of the genotypes averaged over all the seven environments ranged from 25.2 cm^2 (G03) to 34.3 cm^2 (G17 and CSA). Maximum average leaf area was observed for G17 and CSA followed by G01 while minimum was observed for G03 followed by G33 and G25. Among the seven environments, genotypes in Peshawar during 2016-17 on the average produced larger flag leaves having and maximum leaf area, followed by Mansehra in 2017-18 and Kohat in 2016-17 (Figure 2). Flag leaf area was lowest in Mansehra in 2016-17.

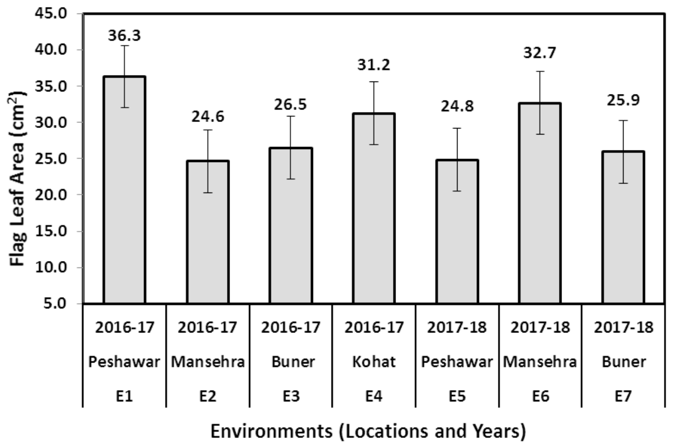

Figure 2: *Flag leaf area averaged over 40 genotypes of wheat, in trials conducted in seven environments of Khyber Pakhtunkhwa, Pakistan during the crop growing seasons of 2016-17 and 2017-18. Error bars are for 1% LSD (4.3 cm^2).*

Straw yield

F-values for environments and genotype × environment interaction sources of variation in combined ANOVA were highly significant for straw yield (Table 1) indicating that straw yield was highly influenced by the environments and the performance of genotypes changed with the changes in the environment. Analysis of variance revealed no significant differences among the average straw yields of the genotypes, which shows that differences among the straw yields of the genotypes did not reach statistically significant level. The GEI accounted for 4.38% of the total variation, however, its significance showed that the performance of the genotypes was not the same across environments; further partitioning in ANOVA showed that G × (irrigated versus rain-fed environments) interaction was also significant at the 1% level of probability. Environments sum of square contributed 89.09% to the total sum of squares signifying that mean straw yield was more influenced by environment and the phenotypic variation present in the trait is mostly due to the effect of the environments. Further partitioning of the environmental variance into single degree of freedom irrigated versus rain-fed environments contrast in ANOVA showed that the contrast was highly significant.

Perusal of the GEI means showed that straw yield of the genotypes in the seven environments, varied between 1013 kg ha^{-1} produced by G28 at Buner in 2017-18 (E-07) and 13722 kg ha^{-1} produced by G01 at Mansehra in 2016-17 (E-02) (Table 4). Within environments, straw yield of the genotypes ranged from 7583 to 13125 kg ha^{-1} in E-01; 10241 to 13722 kg ha^{-1} in E-02; 2433 to 6293 kg ha^{-1} in E-03; 2731 to 5672 kg ha^{-1} in E-04; 5193 to 10067 kg ha^{-1} in E-05; 8381 to 12381 kg ha^{-1} in E-06 and 1013 to 3900 kg ha^{-1} in E-07. Maximum straw yield was observed for G01 in E-01 and E-02 (13125 and 13722 kg ha^{-1} respectively), G16 in E-03 (6293 kg ha^{-1}), G02 in E-04 (5672 kg ha^{-1}), G01 in E-05 (10067 kg ha^{-1}), G22 in E-06 (12381 kg ha^{-1}) and G19 in E-07 (3900 kg ha^{-1}). Though the F-test for the main effect of genotypes was not significant, average straw yield of the genotypes across all seven environments ranged from 6743 kg ha^{-1} to 8413 kg ha^{-1}. Maximum mean straw yield was observed for G01 (8413 kg ha^{-1}), followed by G06 (8241 kg ha^{-1}) and G17 (8151 kg ha^{-1}) while minimum was observed for G08 (6743 kg ha^{-1}), followed by Morocco (6849 kg ha^{-1}) and G28 (6907 kg ha^{-1}).

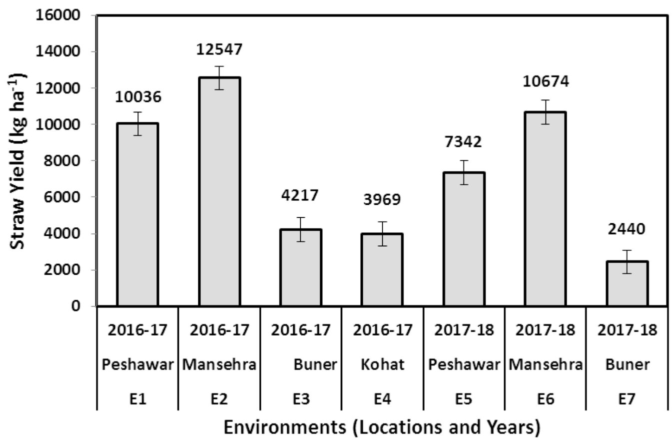

Figure 3: *Straw yield averaged over 40 genotypes of wheat, in trials conducted in seven environments of Khyber Pakhtunkhwa, Pakistan during the crop growing seasons of 2016-17 and 2017-18. LSD 5% for environments is 652.*

Mean straw yield of the 40 genotypes across seven environments revealed that highest straw yield of 12547 kg ha^{-1} was produced at Mansehra in 2016-17 and the lowest yield of 2440 kg ha^{-1} was recorded at Buner in 2017-18 (Figure 3).

Table 2: *Mean plant heights (cm) of 40 wheat genotypes planted in seven environments (four irrigated and three rain-fed) of Khyber Pakhtunkhwa, during 2016-17 and 2017-18.*

Genotype	Environments							
	Peshawar 2016-17	Mansehra 2016-17	Buner 2016-17	Kohat 2016-17	Peshawar 2017-18	Mansehra 2017-18	Buner 2017-18	Mean
	E1	E2	E3	E4	E5	E6	E7	All Env's
CSA	92.3	92.3	79.0	75.6	97.4	77.0	81.5	85.2
G01	86.9	93.7	69.8	71.7	86.4	85.9	71.5	81.3
G02	103.8	95.3	76.1	83.3	97.1	95.6	76.8	90.4
G03	105.1	92.3	72.6	74.1	94.8	86.4	74.5	86.3
G04	102.5	94.3	77.0	78.6	97.8	86.7	83.7	88.9
G05	103.0	88.0	84.9	83.3	94.6	73.8	81.2	87.2
G06	101.1	96.7	76.1	78.8	99.2	83.0	74.0	87.6
G07	107.4	89.0	76.3	80.0	105.4	87.4	83.3	90.2
G08	96.1	90.3	74.4	80.9	94.1	91.4	79.3	87.0
G09	100.8	92.7	77.1	85.0	99.6	89.2	82.8	89.9
G10	90.1	96.7	72.7	76.7	100.4	83.9	78.7	85.9
G11	109.2	97.0	78.4	78.8	102.0	86.0	82.5	91.0
G12	98.1	95.7	79.1	80.7	101.6	83.1	83.5	89.1
G13	100.9	90.0	77.3	83.3	100.9	86.8	82.7	89.1
G14	90.6	92.7	80.2	80.9	87.8	82.9	83.3	85.6
G15	99.7	94.3	78.6	82.7	88.3	88.8	84.3	88.3
G16	98.3	94.3	78.4	83.2	96.1	81.8	81.0	87.9
G17	108.1	91.0	75.7	85.7	97.8	81.3	81.2	89.1
G18	94.5	93.0	80.2	83.0	100.3	77.9	80.2	87.4
G19	102.7	94.3	78.6	80.1	102.3	83.6	84.8	89.7
G20	92.8	87.0	79.9	81.1	93.6	80.9	81.8	85.5
G21	91.5	94.3	72.5	75.1	89.0	75.3	74.7	82.1
G22	87.7	92.0	77.9	73.6	88.0	79.8	79.3	82.8
G23	99.3	88.3	78.1	73.0	94.4	73.7	77.2	83.7
G24	95.4	91.7	78.1	85.2	94.4	85.2	77.7	87.3
G25	89.9	94.3	72.4	72.4	88.4	75.8	78.0	81.8
G26	106.8	95.0	76.6	82.6	92.7	86.4	80.0	89.0
G27	89.0	90.3	77.6	77.9	92.9	78.6	82.3	84.2
G28	98.3	92.0	73.9	83.2	100.7	88.6	86.5	89.1
G29	104.2	96.3	81.9	83.8	98.4	85.0	73.8	89.8
G30	90.5	89.0	74.2	70.0	94.1	77.8	82.3	82.6
G31	105.0	97.0	77.1	80.3	95.3	90.9	86.7	90.5
G32	95.2	94.3	77.9	82.2	100.0	88.4	84.0	89.1
G33	93.2	91.7	66.4	74.7	96.1	81.3	74.7	83.0
G34	94.8	92.0	74.8	80.7	91.6	80.9	82.8	85.5
G35	100.5	96.3	75.9	79.6	100.1	81.6	81.0	88.2
Morocco	107.0	88.0	78.1	79.9	94.7	78.1	85.0	87.4
Atta Habib	101.7	87.3	76.5	74.8	101.0	76.9	77.8	85.5
Ghanimat	99.5	95.3	72.3	72.7	103.3	81.1	79.7	86.6
Siran	102.5	94.0	74.6	75.4	101.4	79.0	81.0	87.2
LSD's§	7.7	6.2	6.0	7.0	6.3	6.6	7.6	2.5

§ LSD 5 % values for each of the seven environments. LSD 5% for GE is 6.7.

Table 3: *Flag leaf area (cm²) of 40 wheat genotypes planted in seven environments (four irrigated and three rain-fed) of Khyber Pakhtunkhwa, during 2016-17 and 2017-18.*

Genotype	Environments							
	Peshawar 2016-17	Mansehra 2016-17	Buner 2016-17	Kohat 2016-17	Peshawar 2017-18	Mansehra 2017-18	Buner 2017-18	Mean
	E1	E2	E3	E4	E5	E6	E7	All Env's
CSA	50.7	27.6	29.3	34.0	29.2	36.2	32.4	34.3
G01	38.8	35.1	21.7	43.4	32.1	34.0	30.5	33.8
G02	29.0	36.0	25.1	35.1	32.6	34.6	25.3	31.4
G03	35.5	21.2	16.7	28.6	20.6	28.5	25.7	25.2
G04	29.8	23.7	26.4	29.4	23.1	29.8	22.6	26.6
G05	38.6	21.7	30.9	35.4	24.5	31.6	24.7	29.9
G06	33.0	22.1	29.9	35.5	23.3	32.0	22.4	28.6
G07	41.6	24.0	27.2	34.4	27.2	39.7	28.2	31.9
G08	29.0	21.4	25.2	29.0	25.9	31.0	23.0	26.5
G09	35.8	22.2	27.4	33.5	25.9	33.6	23.5	29.1
G10	34.1	20.7	32.8	33.3	26.3	37.5	23.7	30.1
G11	28.2	23.5	26.0	21.6	29.8	32.7	25.0	26.8
G12	31.8	21.1	23.9	29.7	25.7	29.5	23.0	26.5
G13	38.4	24.4	28.7	25.2	23.7	34.4	22.8	28.5
G14	38.4	23.3	29.7	20.5	21.7	30.3	22.2	26.8
G15	41.1	22.5	22.5	33.2	21.4	40.5	25.5	29.7
G16	40.8	27.1	27.5	29.7	25.7	33.9	28.8	30.6
G17	45.2	29.5	32.3	37.2	27.1	38.9	27.4	34.3
G18	39.4	26.8	31.5	28.4	22.4	31.0	27.2	29.7
G19	40.9	28.5	23.7	28.8	26.5	33.4	24.3	29.7
G20	44.9	26.6	24.2	38.3	27.5	32.5	24.0	31.5
G21	33.0	25.4	23.4	34.3	19.8	30.5	27.5	27.7
G22	33.1	23.1	32.3	23.7	23.3	36.3	26.5	28.4
G23	33.9	24.4	22.7	24.9	21.1	33.0	25.9	26.6
G24	42.0	23.5	21.8	32.0	26.7	32.9	26.1	29.4
G25	32.8	21.3	25.2	28.0	20.5	29.1	24.8	26.0
G26	30.1	25.9	32.4	28.5	22.8	26.1	23.6	27.2
G27	37.2	23.9	27.0	25.2	21.7	34.3	28.6	28.2
G28	37.1	26.1	30.4	31.4	21.5	32.5	28.0	29.7
G29	38.5	28.3	27.1	28.3	25.9	38.8	31.9	31.2
G30	29.4	23.0	23.0	32.8	25.1	27.1	24.4	26.5
G31	33.5	26.8	31.7	28.6	26.3	31.7	30.5	29.9
G32	28.3	21.0	26.7	31.2	22.9	27.0	25.0	26.1
G33	33.8	21.3	24.6	27.3	21.4	23.0	26.9	25.4
G34	41.0	25.8	29.6	42.8	25.7	37.6	26.0	33.0
G35	38.2	23.5	21.2	26.7	23.5	32.7	26.8	27.5
Morocco	36.1	25.2	28.0	43.0	24.5	34.1	24.9	31.1
AttaHabib	40.4	22.6	22.3	30.0	27.4	33.4	27.7	29.2
Ghanimat	30.9	20.5	23.7	34.9	28.6	33.7	25.6	28.4
Siran	36.3	25.0	24.8	31.6	22.1	27.7	24.4	27.6
LSD's §	7.1	5.6	7.8	7.9	5.9	7.1	5.6	2.6

§ LSD 5 % values for each of the seven environments. LSD 5% for GE is 6.9.

Table 4: *Straw yield (kg ha^{-1}) of 40 wheat genotypes planted in seven environments (four irrigated and three rain-fed) of Khyber Pakhtunkhwa, during 2016-17 and 2017-18.*

Genotype	Environments							
	Peshawar 2016-17	Mansehra 2016-17	Buner 2016-17	Kohat 2016-17	Peshawar 2017-18	Mansehra 2017-18	Buner 2017-18	Mean
	E1	E2	E3	E4	E5	E6	E7	All Env's
CSA	10083	13352	3642	3611	8574	11821	2496	7912
G01	13125	13722	2436	4676	10067	11019	1558	8413
G02	11639	13130	3156	5672	5193	11533	2183	7767
G03	10708	11944	5502	2731	5789	11144	1846	7357
G04	9444	11759	3189	3808	5759	10992	3338	7077
G05	10236	12222	3502	4240	7111	10619	2858	7476
G06	11208	12704	4349	4006	9319	11558	2700	8241
G07	11528	12778	4637	3826	7626	10891	1788	7872
G08	10069	10815	3193	3960	5852	9708	2033	6743
G09	9167	12815	4353	4094	8970	8705	2713	7487
G10	9778	13000	5747	3614	8274	9348	2392	7703
G11	10181	11759	4644	3724	6470	11131	1963	7383
G12	9292	10241	4924	4697	8259	10792	1913	7422
G13	9667	12370	3773	3772	8193	11350	2975	7666
G14	10694	12852	4680	3946	5778	10376	2792	7528
G15	10167	13685	4553	3390	5707	11559	3221	7681
G16	10264	12148	6293	4739	7389	10678	3096	8036
G17	10750	13407	5168	4286	8300	10997	2150	8151
G18	10014	13204	5944	4039	7756	10728	1954	7948
G19	10875	13537	4771	4192	8915	9208	3900	8115
G20	9875	12037	4592	3549	7304	10231	2588	7397
G21	9028	12889	3891	3993	7774	10172	1692	7331
G22	9389	11759	4397	3140	7263	12381	2821	7531
G23	10403	12778	4702	3853	7393	11326	2433	7811
G24	10000	13389	2433	4382	8259	9173	1971	7343
G25	8681	13056	3964	4056	6370	10014	3196	7241
G26	10333	12167	4494	3783	6600	10997	1771	7433
G27	8958	12481	4461	4303	6563	11181	3008	7493
G28	7583	12815	4549	3313	5978	11135	1013	6907
G29	9417	13074	4889	4317	5541	11203	1425	7408
G30	9264	12815	3276	4096	8133	11342	3138	7653
G31	10042	13019	3876	3294	7600	10972	3188	7639
G32	9917	12926	4320	4085	6622	10519	1996	7458
G33	9319	12944	3813	3456	6078	10672	1183	7061
G34	10847	12278	3736	4419	7372	10758	2513	7663
G35	11000	11222	4664	4203	8615	10939	2788	7875
Morocco	7903	11218	2607	4226	7978	10126	2404	6849
AttaHabib	10569	12000	3462	3571	8000	10914	2396	7517
Ghanimat	9975	13093	3233	4104	6726	10385	3067	7434
Siran	10056	12481	4864	3588	8222	8381	3142	7453
LSD's §	1941	1677	1951	902	2099	1764	620	651

§ LSD 5 % values for each of the seven environments. LSD 5% for GE is 1722.

Links Researchers

Table 5: *Biological yield (kg ha[-1]) of 40 wheat genotypes planted in seven environments (four irrigated and three rain-fed) of Khyber Pakhtunkhwa, during 2016-17 and 2017-18.*

Genotype	Environments							
	Peshawar 2016-17	Mansehra 2016-17	Buner 2016-17	Kohat 2016-17	Peshawar 2017-18	Mansehra 2017-18	Buner 2017-18	Mean
	E1	E2	E3	E4	E5	E6	E7	All Env's
CSA	14444	17778	5309	5000	12222	17500	3742	11212
G01	15417	17222	3547	5833	13148	15278	3400	10907
G02	13611	16296	4622	6528	7037	16111	3658	9997
G03	15556	15556	8236	3889	8519	16944	3313	10636
G04	13333	15185	4900	5556	8704	15833	4950	10022
G05	14583	16111	5147	5833	10185	16111	4271	10623
G06	15139	16852	6638	5417	12593	17778	3988	11561
G07	16528	16852	6937	5139	11296	16667	3546	11367
G08	14583	14444	4904	5556	8704	14722	3296	9767
G09	12917	17037	6776	5417	12593	13889	4513	10745
G10	14028	16852	8747	4722	12037	15000	3854	11093
G11	14583	15370	6756	5417	9630	15833	3371	10475
G12	14306	13519	7436	6528	11481	15833	4367	10802
G13	14028	16296	5596	5694	10741	16111	5425	10812
G14	14722	16667	7236	5556	8519	15278	4867	10683
G15	13750	18148	7264	5000	7963	16944	4854	10846
G16	13333	16111	9782	6389	10741	15556	4879	11275
G17	16111	17407	7612	5833	11852	15556	3871	11543
G18	15139	17407	8678	5694	10741	15556	3650	11347
G19	16111	17778	6638	5833	12407	13889	5842	11483
G20	14444	15556	7103	5139	10556	15000	4179	10588
G21	14306	16667	6402	5417	10556	15278	3063	10600
G22	13472	15370	6774	4306	10000	17778	4617	10617
G23	15000	16481	6880	5139	10926	15833	5013	11040
G24	15972	17593	3744	5833	12037	14444	3671	10811
G25	12639	17407	6231	5417	8333	14722	4875	10200
G26	15139	16481	7272	5278	9259	15556	3829	10731
G27	12917	16481	7039	5556	9630	16389	4792	10681
G28	11944	16852	6838	4583	7778	16111	2663	9882
G29	13611	17037	7267	5972	8148	16111	2871	10509
G30	13611	16852	5031	5417	11296	16389	5129	10802
G31	15000	17407	5964	4861	11296	16111	5188	11115
G32	14444	16852	6476	5694	9074	15833	3242	10580
G33	15694	16667	5647	5833	9630	15000	5000	10771
G34	16111	15000	7264	5833	12037	16944	5304	11509
G35	11019	15023	3851	5278	10556	14167	4583	9442
Morocco	15000	17037	4833	5000	9815	16111	4438	10613
AttaHabib	14028	17222	6036	4583	8148	15556	2304	10066
Ghanimat	15000	15741	5329	5000	11667	17222	4217	10915
Siran	15000	16296	7998	5139	12037	17222	5146	11568
LSD's §	2319	2062	2811	1221	2877	1927	732	840

§ LSD 5 % values for each of the seven environments. LSD 5% for GE is 221.

Biological yield

Probability of F-value for genotypes showed significant differences (P≤0.05) among biological yields of the genotypes (Table 1) showing that the genotypes produced different amount of above ground biomass. Main effects of environments and interaction effects were highly significant for biological yield. Maximum contribution to the total sum of squares was made by environments (89.80%), followed by GEI (4.04%) and genotypes (1.04%). The total variation present in the above ground biomass was mainly due to the effects of the environmental conditions. Significant GEI suggested that fluctuating external factors had dissimilar effects on the genotypes and thus the same genetic makeup expressed differently in different environments.

Across all the environments included in the study, highest biological yield was observed for G15 (18148 kg ha^{-1}) in E-02 while lowest biological yield was observed for Atta Habib (2304 kg ha^{-1}) in E-07 (Table 5). In E-01 biological yield ranged from 11019 kg ha^{-1} to 16528 kg ha^{-1} with a grand mean of 14414 kg ha^{-1}, in E-02 from 13519 kg ha^{-1} to 18148 kg ha^{-1} with a grand mean of 16473 kg ha^{-1}, in E-03 it ranged from 3547 kg ha^{-1} to 9782 kg ha^{-1} with a grand mean of 6418 kg ha^{-1}, in E-04 from 3889 kg ha^{-1} to 6528 kg ha^{-1} with a grand mean of 5403 kg ha^{-1}, in E-05 from 7037 kg ha^{-1} to 13148 kg ha^{-1} with a grand mean of 10347 kg ha^{-1}, in E-06 from 13889 kg ha^{-1} to 17778 kg ha^{-1} with a grand mean of 15854 kg ha^{-1} and in E-07 from 2304 kg ha^{-1} to 5842 kg ha^{-1} with a grand mean of 4194 kg ha^{-1}. Mean values for biological yield averaged over all locations and years ranged from 9442 kg ha^{-1} to 11568 kg ha^{-1} with a grand mean of 10756 kg ha^{-1}. The check cultivar Siran exhibited maximum biological yield averaged over all environments (11568 kg ha^{-1}), followed by G06 and G17 (11561 and 11543 kg ha^{-1}, respectively). G35 had minimum above ground biomass followed by G08 and G28 (9442, 9767, 9882 kg ha^{-1}, respectively).

Overall, the genotypes included in the study had more biological yield in Mansehra as compared to other locations. A difference of 3782 kg ha^{-1} was observed in the average biological yield of Mansehra and Peshawar whereas a difference of 10857 kg ha^{-1} and 10760 kg ha^{-1} was observed between Mansehra and Buner and Mansehra and Kohat, respectively (Figure 4). Considering the mean biological yield of all the genotypes across the environments highest biological yield was produced in Mansehra during 2016-17 followed by Mansehra in 2017-18, while lowest average biological yield was produced in Buner in 2017-18.

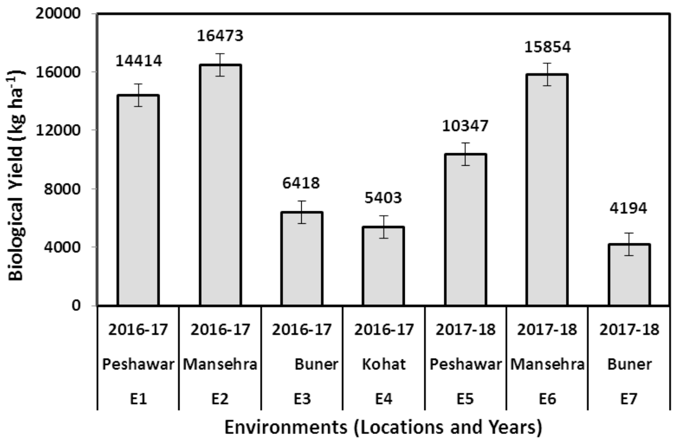

Figure 4: *Biological yield averaged over 40 genotypes of wheat, in trials conducted in seven environments of Khyber Pakhtunkhwa, Pakistan during the crop growing seasons of 2016-17 and 2017-18. Error bars are for 1% LSD (772).*

The increase in agriculture production in recent past few decades has generally been in pace with the demands however the yields of a number of crops are reaching a plateau (Raines, 2011). The current scenario of rapidly increasing population and climate change effects is resulting in more pressure on the production of agriculture crops. One important element of plant productivity that is not much used directly to select for improved yield is photosynthesis (Raines, 2011). Photosynthetic products are the primary elements of plant productivity, increasing photosynthetic rate is considered an important trait for increasing biomass and biological yield (Parry *et al*., 2011; Zhu *et al*., 2010). Previous studies show that agronomic traits such as plant height, harvest index and total biomass have also contributed to improvement in grain yield (Gao *et al*., 2017). In the present study, exotic bread wheat lines were evaluated for vegetative growth traits, as total biomass is a function of the total photosynthetic activities of the plant (Driever *et al*., 2014) and flag leaf area has been identified as valuable trait in breeding programs and a major contributor to grain yield (Alqudah and Schnurbusch, 2015; Driever *et al*., 2014).

Breeding and selection for ideal plant traits to increase crop production is challenging due to the presence of genotype × environment interactions (Sohail *et al*., 2016; Sharma, 1993). For assessing performance of genotypes, they are generally tested over a range of different environments to evaluate the variation in performance in diverse set of conditions (Ahmadi *et al*., 2012) as the accuracy of independent field trials is low (IRRI, 2006) and the G × E interactions hampers the actual performance of the genotypes. In the present multi-environment trial, pooled analysis of variance showed that the main effects of genotype and environment were significant for plant height, leaf area and biological yield and for the straw yield the main effect of the environment was significant whereas the main effect of the genotypes was statistically not significant (Table 1). These results indicate that the genetic makeup of the genotypes as well as the environmental conditions were responsible for the variation observed in the vegetative growth traits of the genotypes. For all the studied traits main effect of the environments was an important source of variation as indicated by the higher contribution of environment sums of squares to the total sum of squares. This shows that the environments in which the genotypes were tested were diverse and had significantly affected the performance of the genotypes.

Plant height is a measure of vertical growth and it is needed to place leaves at different positions for proper light interception and photosynthesis, however, very tall varieties are prone to more lodging under irrigated conditions and very short varieties do not perform well under limited water conditions. Moreover, wheat genotypes with plant height reduced to a certain level has increased genetic gains in wheat and has significantly contributed to increased wheat productivity globally (Tshikunde *et al*., 2019; Zhang *et al*., 2016). Plant height in this study was affected by environment, genotypes and G x E interaction. Plant height in different environments ranged from 76 to 98 cm; average height of the different genotypes ranged from 83 to 91 cm, in the GE two-way table plant height ranged from 66 to 109 cm. G02, G31 and G11 produced maximum mean plant height (Table 2). Measuring the leaf area of plants is important for measuring growth and vigor of plants and leaf area especially the flag leaf area is the primary source of energy and mass exchange between the atmosphere and plants (Fang and Liang, 2008). Leaf area is measured in plants to evaluate processes such as canopy evapo-transpiration, biomass accumulation and photosynthesis (Ahmad *et al*., 2015). Flag leaf area is important as it contributes major part of assimilates for grain filling and thus contributes to yield. Leaf area is considered to be an indicator of crop growth, development, and plant health, and has a strong relationship with these traits in wheat and barley (Alqudah and Schnurbusch, 2015). Several studies report that appropriate flag leaf size could promote development of high grain yield potential (Zhao *et al*., 2018). Leaf area of the genotypes as averaged over all seven environments ranged from 25.2 to 34.3 cm^2. Maximum mean leaf area was observed for G17 and CSA followed by G01 while minimum was observed for G03 followed by G33 and G25 (Table 3).

Wheat straw is an important component of the crop, it serves as a main source of animal feed in areas/time of year where green fodder is not available; it is also used in combination with green forage to fulfill the nutritional requirements of the animals (Kumar *et al*., 2013) especially in Pakistan and other Asian countries. Cereals straw is recognized as a significant source of renewable energy, (Zajac *et al*., 2013), in some advanced countries like USA, there is an increasing demand for wheat straw by livestock farmers to be used in feed rations (Gross, 2016). Wheat straw also serves as an important raw material for bioethanol (renewable fuel), the use of which can reduce the production of carbon dioxide and also lessen the dependency on fossil fuels (Dai *et al*., 2016). Wheat straw can also be used for animal bedding, paper making to save trees, cap making, basket making, composting, packing material and mushroom cultivation. In the present study, though the seven single site ANOVAs for the different environments showed significant differences among straw yields of the genotypes (as shown by LSDs in each column for environment in Table 4); main effect of the genotypes in combined ANOVA for straw yield was not significant but the GEI for straw yield was significant indicating that differences were found among the straw yields of the genotypes in the different environments and rankings of the straw yields of the genotypes were different in the different environments with different genotypes producing maximum and higher straw yields in different environments as shown in each column of Table 4, However, the environmental conditions at each site had much greater effect on straw yield of the genotypes (Figure 3).

The above ground biomass known as biological yield is a useful selection criteria for improving grain yield in wheat and it has a high economic value as well (Jimenez-Berni *et al*., 2018; Sharma, 1993). In developing countries genotypes having high biological yield are more preferred by farmers as such genotypes produce more grains as well as non-grain plant parts (Sharma, 1992). G06 and G17 among the tested lines exhibited maximum above ground biomass averaged over all environments. Biological yield of the genotypes differed significantly across environments. Biological yield ranged from 18148 kg ha^{-1} for G15 in E-02 to 2304 kg ha^{-1} for check line Atta Habib in E-07. The trend of the biological yield produced by the genotypes in different environments showed that majority of the genotypes produced higher biomass in Mansehra and lower in Buner (Figure 4). The reason for low dry matter accumulation in genotypes in Buner could be due to the scarcity of water in early vegetative growth stages.

Conclusions and Recommendations

Significant differences were found among the genotypes for plant height, leaf area and biological yield whereas there were non-significant differences among the straw yield of the genotypes. Main effects of the environments were also highly significant for all the traits. GEI were significant for all the studied traits showing that performance of the lines varied under different environments. It can be concluded from these results that genetic makeup, environmental differences as well as their interaction were responsible for the phenotypic differences in then genotypes. This has an important implication for wheat breeders and these can be exploited by breeders for variety development and varietal improvement programs. Exotic lines G06 and G17 produced more biological yield; G11, G31 and G02 produced taller plants and G17 and G01 produced larger leaves. Grain yield can be improved by increasing biological yield as it is the product of biological yield and harvest index. These lines can be used in crossing programs to combine desirable traits in single line, or to transfer these traits to other high yielding and superior varieties.

Novelty Statement

This study highlights the importance of otherwise neglected straw yield and other vegetative growth traits of bread wheat.

Author's Contribution

Hafsa Naheed: Conducted the experiments, collected, interpreted and analysed the data and wrote the manuscript.
Hidayat-Ur-Rahman: Supervised the research, provided research material, reviewed the manuscript.

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

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