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Original Research Article

EXPLORING THE RELATIONSHIP BETWEEN PLANT HEIGHT AND YIELD-CONTRIBUTING ATTRIBUTES OF WHEAT IN DROUGHT CONDITIONS

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Abstract *Plant height is the most dynamic yield-affecting trait which has strong genetic and phenological associations with yield performance in wheat. The objective of the study was to explore the effect of plant height on spike yield by investigating the interrelationship between height and yield components of ninety wheat genotypes under a drought environment. Different statistical procedures including correlation, regression, path coefficient, principle component, biplot, and cluster analysis were performed to dissect the associative role of height and yield components in setting the yield potential of wheat plants. High positive correlation and direct effects are seen for spike yield from seed weight (r = 0.73) and seed number (r = 0.60) with a participatory contribution of 58% and 40%, respectively. But plant height is negatively associated with thousand seed weight (-0.22*) and spike yield (-0.15) in such a way that each additional unit (1cm) of height reduces 0.11 g thousand seed weight and 0.06 g spike yield due to negative regression. PC1 and PC2 associate height and yield components respectively and both types of traits moderately oppose each other for simultaneous improvement. Highly tall and short plants were observed with low yield potential under water-limited resources due to strong negative effects either on seed weight or number. An increase in height favors seed number but reduces enough seed weight to cause comparative losses. Intelligent allocation of plant resources to height or spike defines the plant yield potential. Plants with moderate height ranging from 74-83 cm were seen with the best yield potential among five different classes of height. Genotypes HM729, HM829, and HM644 belonged to this class and their better yield potential was due to the balance ratio of seed weight and number. This work would help direct our breeding programs for the improvement of the height-oriented yield potential of wheat.*

Keywords*:* *plant height; yield contributing traits; Wheat; Drought conditions; association*
List of Abbreviations— **PH** (plant height), I**nt.L** (Inter-nodal lengths), **Pd.L** (Peduncle length), **SL** (Spike length), **SPS** (Seeds per spike), **TSW** (Thousand seed weight), **SY** (Spike yield)

1. Introduction

Wheat is a rich source of essential dietary constituents and widely grown around the world to fulfill human's food requirements (Sehgal et al., 2012). Drought is a most significant environmental consequence of climatic changes due to its colossal losses among other stresses (Asadi et al., 2013). Wheat morphology especially plant height and spike development is badly affected under water deficit conditions. Drought is responsible for height reduction and low dry matter production due to a decline in photosynthetic activity (Day and Intalap, 1970). It also affects the yield-contributing traits of wheat like several tillers per plant, grain weight, and grains per spike (Farooq *et al*., 2009). A plant facing a drought spell at the reproductive stage reduces grain weight due to drought-oriented desiccation in grains and the early maturity of wheat crops (Sayar et al., 2010).

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Plants respond to stresses by limiting growth and activating their defense which is necessary to divert their energy towards stress tolerance. Negative effects of drought are tackled by managing reactive oxygen species (ROS) detoxification, and maintaining homeostasis and membrane stability at a cellular level (Kocheva *et al.*, 2014). Phonologically, some characteristics like plant height, number of tillers per plant, spikelets per spike, grains per spike, 1000-grain weight, and days to maturity are reported to be connected with drought tolerance in wheat (Ahmad et al., 2006; Farooq et al., 2009). An optimum plant height between 0.7 to 1.0 m is reported best for getting maximum yield benefits under water scarcity (Spink et al., 2004). Height affects the plant's performance especially in the context of yield and quality of grains (Skylas et al., 2000). Shortening of height increases harvest index and lodging stability but severe dwarfism is associated with a reduction in yield (Berry and Berry, 2015; Tilman et al., 2011). Height reduction is a function of different reducing height (Rht) genes which are positively associated with productivity under water deficit conditions (Wen et al., 2013). Different height and yield-related genes are located on 17 wheat chromosomes out of 21. Significant phenotypic correlations between height and yield contributing traits are defended by genetic associations between their candidate genes and QTLs within the same linkage group (Zhang et al., 2013). These associations provide an efficient gene pyramiding opportunity for ideal plant height and yield potential (Wu et al., 2012). Selection for yield-contributing genes/traits provides an associative selection of height-responsible genes/traits and vice versa (Würschum et al., 2015). Plant height is positively associated with spike yield through the improvement of spike traits of wheat plants in a normal environment. Long stature facilitates more spike length and seed number (Edae, 2013), while short plant size is reported with more fertile tillers in wheat (Daoura et al., 2013). However, stress induces unsatisfactory effects on plant height and spike development to lower yield potential. So, there is a need to work out the associative effect of height on the spike yield of wheat to explore height-dependent yield potential under a drought environment. This study elaborates well on the individual and associative effect of each component of height on different yield-contributing traits of the wheat spike.

2. Material and methods

2.1. Wheat germplasm and site specifications

Ninety distinct wheat genotypes from different geographical regions (Maxico (CYMMIT) Australia, China, and Pakistan) were used in this investigation. Plant material was grown during two consecutive years 2013 and 2014 on an experimental site which is located at latitude 31.43° North, longitude 73.8° East, and 184 m a. s. l. Average Day temperature during experimental seasons (NOV-APRIL) ranged between 18-26°C while the average rainfall was 14.1- 16.5 mm. There was almost no rainfall during earlier months of crop growth in both seasons.

2.2. Experimental design and drought establishment

The experiment was conducted following an augmented design to adjust more number of genotypes. The non-replicated design makes good use of scarce resources. One meter long four rows of each genotype were grown in plots having a gross area of 1 m × 1 m. Rows were 30 cm apart from each other. All recommended agronomic and cultural practices (fertilizing, hoeing, and spacing) were carried out except the irrigation to create a drought environment. To expose genotypes to drought conditions, only the first irrigation was carried out as compared to 3-4 normally given during the season.

2.3. Measurement of plant traits

Each genotype was phenotyped at an appropriate time for plant height/PH (cm), inter-nodal lengths/Int.L (cm), peduncle length/Pd.L (cm), spike length/SL (cm), seeds per spike/SPS, thousand seed weight/TSW (g) and spike yield/SY (g). Measurements of height-related traits were made with a calibrated meter rod at maturity before harvesting of material. Plant height was measured from the base of the plant to the tip of the spike, inter-nodal lengths from the base to the last node of the stem, peduncle length from the last node of the stem to the base of the spike, and spike length was measured from base to tip of spike excluding awns. On the other hand, measurements for yield contributing traits were made after harvesting. Threshing was done with a single-head threshing machine (Todd System Yonkers.N.Y.USA). Seeds per spike and thousand seeds were counted and weighed by automatic seed counter (Sly-C-20140605-1) and electronic weighing balance (Compax, RS232C), respectively. Spike yield was gained after getting an average seed weight of ten spikes from each genotype.

2.4. Statistical analysis

The raw data from all plants were compiled to take mean values for different traits. The average data of both years were used to perform different statistical and biometrical analyses.

2.4.1. Summary statistics and principal component analysis

These analyses were used to study variation present in different traits. Principal component analysis classified whole variability into major components which collectively cause total variation. The first principal component (PC1) explained the largest variability while other principal components (PCs) covered the remaining part of the total variation (Everitt and Dunn, 1992).

2.4.2. Correlation and regression

Correlation and regression analysis were performed (Steel et al., 1997) using IBM SPSS Statistics version 22, and regression plots were also drawn on this software (Velleman and Welsch, 1981).

2.4.3. Path analysis

Path coefficient analysis was performed by considering spike yield (SY) as the effect and all other height and yield components as the cause. Direct and indirect effects of these components were estimated on SY (Dewey and Lu, 1959).

2.4.4. Biplot and cluster

Biplot and cluster analysis were performed using GenStat 10th edition software and Microsoft Office Excel 2007. Five nonhierarchical clusters of plant height were made by using the option between-group sum of squares in GenStat. Genotypes in each cluster were arranged in ascending order for plant height. Respective data of all other traits were placed and pooled for those genotypes that were selected in each height-based cluster. Overall and cluster means were obtained for each trait and used for graphical presentation.

3. Results

3.1. Variability studies

Different statistical values like mean, maximum, minimum, stander deviation, stander error of means (SEM), and coefficient of variation (CV) are given in Table 1. In the present inquiry of 90 wheat genotypes, the average PH was 88 cm while mean Int.L, Pd.L, and EL were 41.2 cm, 34.2 cm, and 12.2 cm, respectively. On the other way, the respective mean values of SPS, TSW, and SY were 60.8, 43.7 g, and 26.6 g. High CV percentage (CV% >10) and range of variability were found around the mean value of each trait. Ear length (17.5%) and SY (15%) showed the highest CV percentage followed by Int.L, TSW, PH, Pd.L and SPS.

Table 1. Summary statistics for height and yield contributing traits of 90 wheat genotypes

Character	Mean	Min-Max	SD	SEM	C.V%
PH (cm)	88.0	53 – 120	10.0	1.00	12.0
Int.L (cm)	41.2	23 – 66	7.2	0.80	12.9
Pd.L (cm)	34.2	19 – 45	4.4	0.50	10.7
EL (cm)	12.2	9 – 18	1.3	0.14	17.5
TSW (g)	43.7	27 – 54	5.3	0.60	12.1
SPS	60.8	48 – 84	6.1	0.60	10.0

3.2. Association studies

Correlation and regression explained well the type and strength of interaction between target traits. Correlation and determination coefficients along with linear regression equation were determined for all interactions of plant height with height and yield components (Table 2). PH showed a very strong, positive, and highly significant association for Int.L (r = 0.89**), Pd.L (r = 0.75**), and EL (r = 0.51**) but had a negative association for TSW (r = -0.22*) on a significant basis. The association of PH with SPS (r = 0.04$^{N.S}$) and SY (r = -0.15$^{N.S}$) was weak and non-significant. The coefficient of determination (R square values) explained that PH was greatly determined by each of its components like Int.L (R^2 = 0.79), Pd.L (R^2 = 0.56), and EL (R^2 = 0.26). But weak R square values between PH and TSW (0.051), SPS (0.002), and SY (0.025) were observed.

Table 2. Correlation and regression coefficients along with regression equation for height and yield contributing traits of wheat

	Correlation (r)	Regression coefficient	Linear Regression equation
	PH (X4)		
Int.L (X1)	0.89 **	0.79	Y= 34.3 + 1.29x
Pd.L (X2)	0.75 **	0.56	Y= 26.8 + 1.78x
EL (X3)	0.51 **	0.26	Y= 37.9 + 4.06x
	TSW (X5)		
PH (X4)	-0.22*	0.05	Y= 57.5 + (-0.11x)
	SPS (X6)		
PH (X4)	0.04 $^{N.S}$	0.002	Y= 58.39+ 0.03x
	SY (Y)		
PH (X4)	-0.15 $^{N.S}$	0.02	Y= 31.83 + (-0.06x)

In a linear model of PH and Int.L, slope coefficient showed that every additional unit of Int.L (1cm) added up 1.29 cm in total plant height within a range of 53-120 cm reported in this study. Similarly, each upcoming unit of Pd.L and EL individually increased PH by 1.78 and 4.06 cm respectively.

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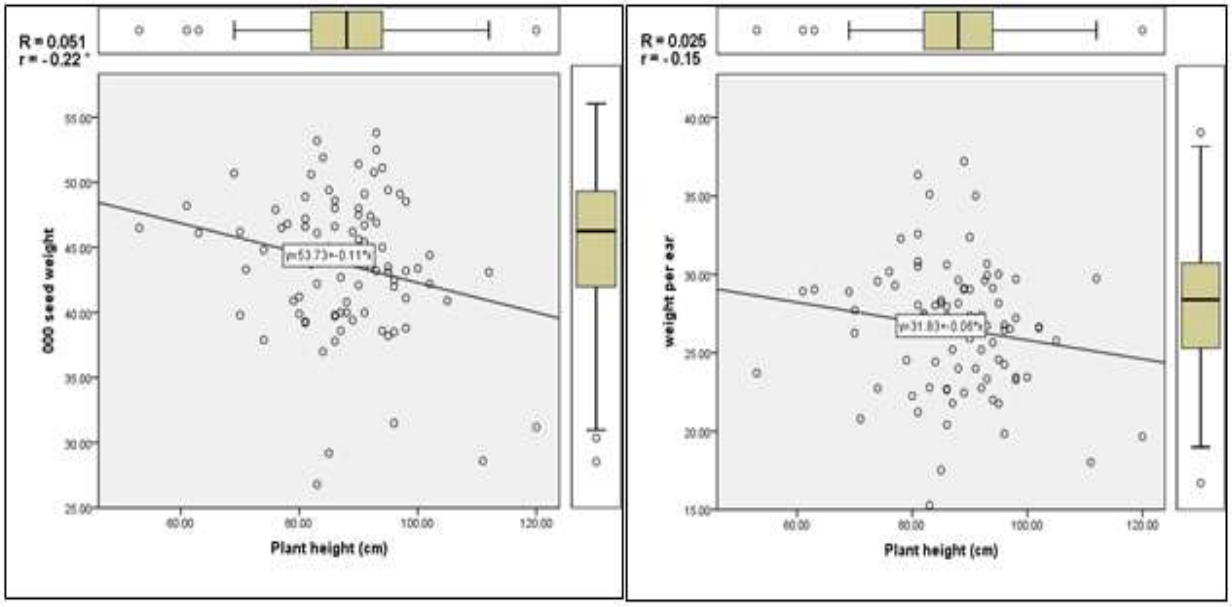

Figure 1. Regression plot of plant height with thousand seed weight and spike yield of 90 wheat genotypes.

Regarding the effects of height on yield contributing traits, every increasing unit (1cm) of plant height decreased 0.11 g and 0.06 g from TSW and SY respectively, while it increased 0.03 SPS (Fig 1).

3.3 Principle component analysis

Phenotypic data of all variables were portioned into three main components (PC1, PC2, and PC3) which significantly made the impact on whole variability (Table 3). The Eigenvalue of each upcoming component was decreased (PC1 = 2.87 > PC2 = 1.88 > PC3 = 1.19) and they collectively covered 84% of the total variability of all variables. PC1 accounted for 41% of total variation followed by PC2 (26%) and PC3 (17). Factor loadings or correlation coefficients of each PC concerning all variables were given in Table 2. PC1 showed a high positive correlation with PH (0.95) and other height components but was negatively associated with yield components. PC2 showed an opposite trend of PC1 where yield components were positively associated with it. PC3 contained a moderate behavior for height and yield components where TSW (0.67) and EL (0.32) were positively correlated with it but Pd.L (-0.41) and SPS (-0.57) had a negative association.

Table 3. Eigen value and the correlation matrix for estimated variables of wheat using principle component procedure

Variables	PC1	PC2	PC3
PH	0.95	0.14	0.27
Int.L	0.74	0.24	0.24
Pd.L	0.65	0.34	-0.41
EL	0.80	-0.01	0.32
TSW	-0.49	0.52	0.67
SPS	0.07	0.75	-0.57
SY	-0.35	0.92	0.14
Eigen value	2.87	1.88	1.19
Proportion	41.00	26.85	17.01
Cumulative %	41.00	67.85	84.87

3.4 Biplot analysis

All accessions were subjected to biplot analysis to study the genotypic behavior of target traits. The biplot was plotted by taking the difference between PC1 and PC2 after scattering the genotypes in their respective suitable environment for height and yield components (Figure 4). The effectiveness of each genotype was determined by its length of OP vector (tangent of a genotype at a specific vector of a trait) for a specific trait. Genotype 85 (HM1026) showed the longest OP vector for height components. This genotype with the highest PH (120 cm) and Int.L (66 cm) had 31.2 g TSW, 63 SPS, and 19.6 g SY. On the shorter side, genotype 44 (HM755) with 53 cm PH was seen with 44.5 g TSW, 51 SPS, and 23.7 g SY. The best genotype for yield components with 44.3 g TSW, 84 SPS and 37.2 g SY was 37 (HM729) which had 89 cm PH. Other genotypes belonging to this category of SY were 61 (HM829), 67 (HM863), and 15 (HM644) which had plant heights 91, 83, and 81 cm respectively.

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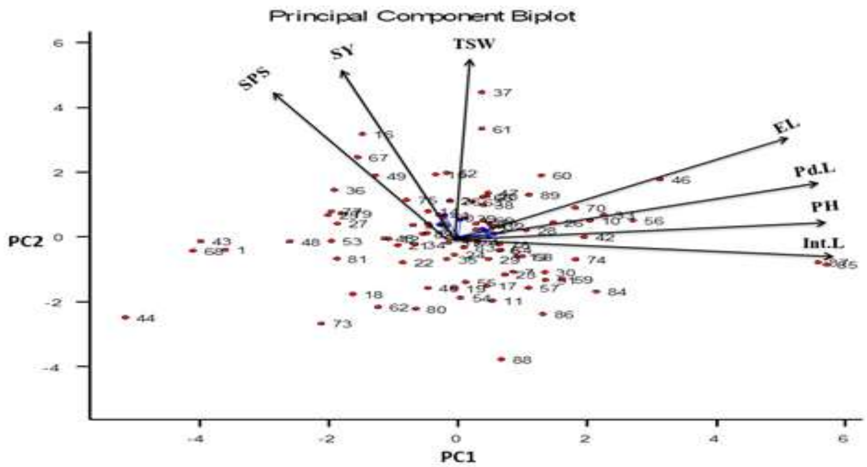

Figure 2. Biplot differential display for height and yield contributing traits of 90 wheat genotypes

3.4 Cluster Analysis

To study the relationship between PH and SY, the total variation in PH was torn into various groups of narrow variability (each cluster represented by mean value) and the best group of PH was selected based on SY. Cluster analysis was performed to make the groups of genotypes that fell under one category of PH. Five clusters (C1→C5) of PH were made in ascending order and associative variability patterns were elaborated for other traits by using this order (Fig. 2). In comparison to the original variability of 90 genotypes, five classes of PH maintained a high proportion of total variability in all traits and provided enough variation for selection of best height class in respect to SY. Clusters maintained 64% of the original variability for PH and showed enough expansion between their respective lines (Fig. 2c).

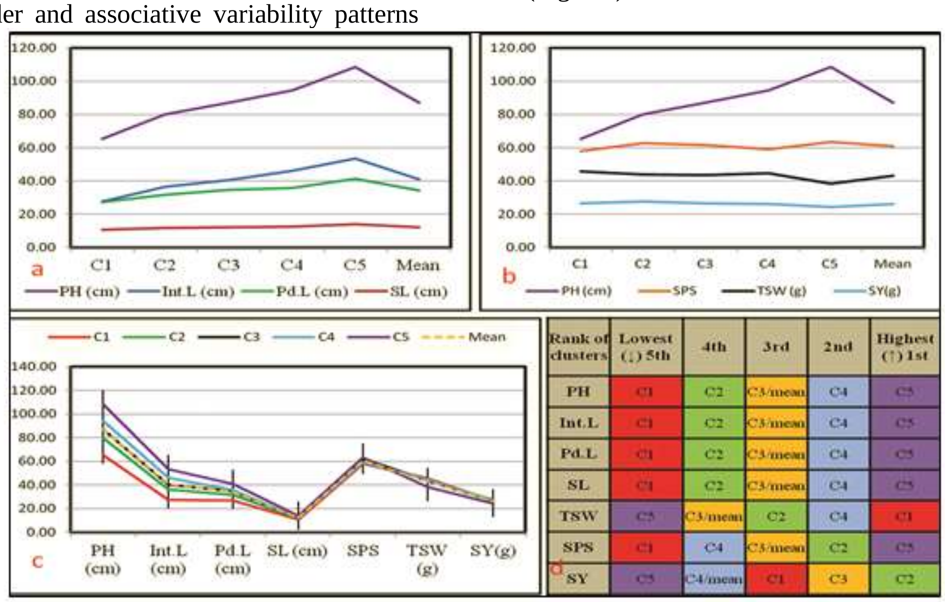

Figure 3. Associative variability pattern between (a) plant height and its components (b) plant height and yield components (c) Comparative trend of height dependent variation in clusters of all traits (d) associative distribution of five clusters for each trait

Int.L retained the highest original variability (60%) for five different plant statures followed by Pd.L (53%), EL (37%), TSW (27%), SPS (15%) and SY (13%). Height-oriented clusters showed a differential response of variability for all traits. This can be seen by the shrinking or expansion of cluster lines on vertical black lines which represent the original variation of 90 genotypes. Trend lines of all height-oriented clusters showed similar patterns of variability at each height component but reversed their order at TSW and SY (Fig. 2c).

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Graphs explain well the associative changes and interrelationship patterns between height and yield contributing traits. Overall means of all traits were represented by C3 except the SY where C4 was close to the mean value (Fig. 2d). Ascending order of PH governed in five groups is given as from C1 < C2 < C3 < C4 < C5 with their respective mean values of 65.2 < 80.1 < 87.3 < 94.4 < 108.4 cm. Inter-nodal lengths followed the same cluster order with their respective means 27.4 < 36.4 < 40.4 < 46.1 < 53.5 cm while five clusters had their mean Pd.L and SL values 27.1 < 31.7 < 34.6 < 35.9 < 41.1 cm and 10.6 < 11.8 < 12.2 < 12.4 < 14 cm, respectively. It was seen that all height components follow the increasing pattern of variability same as the PH (Fig. 2a). The Highest graphical similarity for PH is shown by Int.L which is defended by its strongest association (0.89) and followed by Pd.L (0.75) and SL (0.51). On the other side, cluster order followed by yield contributing traits on increasing trend of height was random for SPS, TSW, and SY (Fig. 2b). Seeds per spike showed order from C1 < C4 < C3 < C2 < C5 with a mean number of seeds 57.8 < 59 < 61.5 < 62.5 < 63.5. Order was almost in the same fashion as PH but only C2 replaced C4 at 2nd position and got the higher rank just after C5 which was 1st among all the clusters for SPS. Thousand seed weights had almost reverse order of SPS and PH from C5 < C3 < C2 < C4 < C1 with respective means of 38.4 < 43.4 < 43.7 < 44.5 < 45.8 g.

Hare, C3 (representative of mean) fell at 4th position but actual replacement was done by terminal clusters of TSW in comparison to PH and SPS (Fig. 2d). An opposite behavior due to a strong negative association (-0.22) between PH and TSW was observed on their trend lines. It is obvious that TSW decreased where SPS increased and vice versa (Fig. 2b). Final ascending order for yield-determining traits like spike yield was C5 < C4 < C1 < C3 < C2 with respective mean values of 24.4 < 26.2 < 26.4 < 26.6 < 27.4 g. Genotypes in a cluster of lowest plant height (C1) ranked at 3rd position for SY. Two high classes of height C4 and C5 ranked lowest with respect to spike yield at 4th and 5th position, respectively. C2 with an average PH of 80.1 cm was the leading one for SY among all the clusters followed by C3 which represented the mean plant height. Comparative yield performance of five different classes of plant height is shown in (Fig. 3). C2 had with best yield components and SY while C5 had the lowest yield potential. Other clusters like C1, C3, and C4 showed differential results for TSW and SPS but had almost the same response for SY.

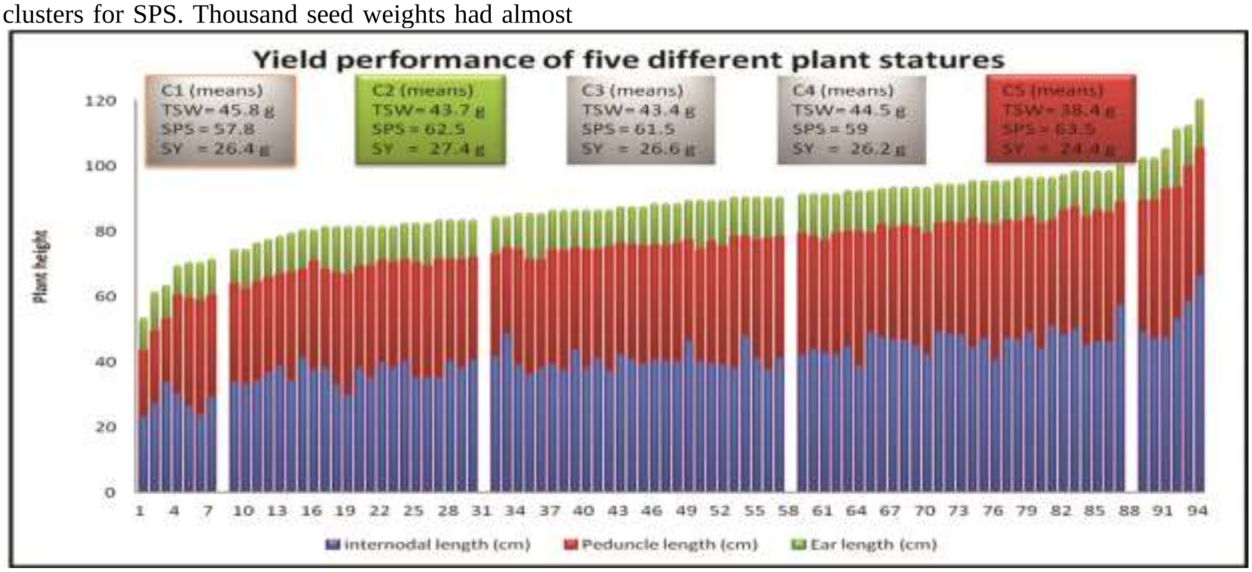

Figure 3. Participatory contribution of inter-nodal lengths (Int.L), peduncle length (Pd.L), and spike length (SL) in plant height (PH) and effect of five different plant statures (C1-C5) on thousand seed weight (TSW), seeds per spike (SPS) and spike yield (SY) for establishing the yield potential (green box → maximum, grey box → medium, red box → minimum).

4. Discussion

The present investigation was carried out to explore the effect of plant height on spike yield. Understanding of different associative changes between height and yield contributing traits helps know the way to spike yield establishment. Plant height is an important phenological trait of wheat to determine yield performance (Griffiths et al., 2012). In wheat, vegetative growth decides the final plant height about high or low biomass production, while reproductive growth sets up the final plant yield

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under vegetative health (Chen et al., 2013; Rebetzke et al., 2012). Different structural and physiological modifications occur during vegetative and reproductive development. Yield-contributing traits respond accordingly to these modifications for long and short plant stature (Gent and Kiyomoto, 1997). Plant growth provides a basis for attaining final body size and yield under normal conditions. Stress induces disturbance in normal growth and development due to an imbalance in internal and external resources (Asif and Kamran, 2011). Plants respond to stresses by limiting growth and activating their defense system through integrated multiple hormonal pathways. Drought is a limitation of water under high temperatures and is associated with the generation of reactive oxygen species (ROS) due to less osmotic potential. ROS attack membranes to break their structure and promote oxidative damage which ultimately lowers the yield potential (Kocheva et al., 2014). Here, defensive mechanisms are needed to tackle the attack of ROS and its relatives. Plant size is important in the context of limited growth and defense activation to achieve suitable results. A plant with a short stature attains its final height soon as compared to a long one and timely shift on defensive behavior against ROS to minimize oxidative damage for reliable yield performance (Selote and Khanna-Chopra, 2006). Furthermore, internal plant adjustments at the molecular level like osmotic regulation and homeostasis also relate to plant size under limited resources. Small cell size requires less cellular osmotic potential to adjust internal mechanisms as compared to large cells of long stature (Blum and Sullivan, 1997).

Generally, short-stature plants are characterized by better performance under limited resources due to high osmoregulation, antioxidant activity, and membrane stability. They also meet their needs somehow more easily than long ones due to fewer food requirements (Kocheva et al., 2014). Tall plants are characterized by higher seed numbers and biomass production. But they accumulate less proportion in spike than dwarf ones which are efficient in the assimilation of photosynthates (Chen et al., 2013). Poor assimilation of tall plants under stress is associated with reduced seed size and weight, while more number of seeds also contributes to the loss of weight due to inter-competition for assimilates. On the other side, dwarf plants show higher seed weight because of efficient assimilation and less number of seeds (Chen et al., 2014). It is obvious from Spike path studies, that SY is the resultant of combined function TSW and SPS in such a way that seed weight makes a higher contribution (58%) to SY than seed number (40%). Both of these components are reported with negative association and intra-competition, especially under limited resources. Our association studies revealed that PH decreases SY due to its significant negative effects on TSW while positive effects on SPS are little. Principle component and biplot analysis help understand the overall and average performance of genotypes for different morphological traits on a graphical presentation. Closely related and distant traits are easily detectable just by an outlook of representing arrowheads. The angular distance between the two representing arrows showed the strength of the association between those traits. Factor loadings are coefficients carried by each principle component and they indicate a correlation between that specific PC and all variables. The strength of correlation indicates how much a variable relates to that specific PC.

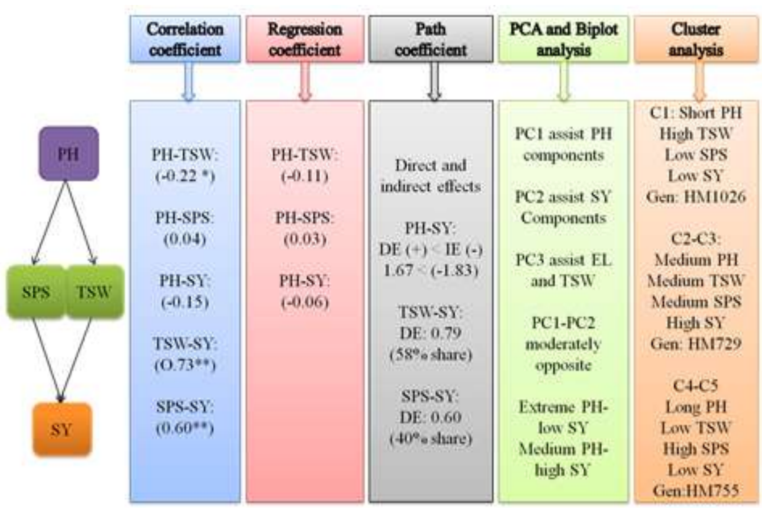

Figure 4. Comparative output with respect to plant height, thousand seed weight, seeds per spike and spike yield from all statistical analyses

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In our results, all height components are near to each other and showed close association with PC1 while yield-related traits are seen with the same trend for PC2. PC1 and PC2 are directed at a right angle to each other which means plant height and spike yield belonged to two different environments. Cluster analysis was performed where clusters represented the behavior of five different plant statures for yield contributing traits. They retain sufficient variability on plant level which makes significant differences on a large scale as per acre yield. In a linear relation of PH and SY, cluster order of spike yield (C5 < C4 < C1 < C3 < C2 / 24.4 < 26.2 < 26.4 < 26.6 < 27.4 g) shows that C5 with maximum PH (108 cm) has minimum yield potential and C2 with moderate PH (80.1 cm) shows maximum spike yield. All other classes of PH (C4, C1, and C3) are showing almost the same response for SY with an average value of 26.4 g (26.2 + 26.4 + 26.6 / 3). Being part of PH, the associative strength and participatory contribution of height components is observed as Int.L > Pd.L > SL. Correlation and regression analysis revealed a strong positive association and determination of plant height from its components. Cluster analysis also proved this interaction as PH and its components share the same ascending sequence of clusters from C1 to C5. Plant height regresses negatively to TSW and SY but has a positive influence on SPS. Seeds per spike and seed weight are the main contributors of SY and both respond differently to five classes of PH. Cluster analysis explored that both extremes of PH are showing low yield potential due to a strong inverse relationship between SPS and TSW. Cluster distribution for ordinal ranks showed that C5 with the longest PH (108.4 cm) although has the highest SPS (63.5 = 1st rank) but the maximum reduction in TSW (38.4 g = 5th rank) causes the lowest SY (24.4 g = 5th rank) of this class. On the other way, C1 with the shortest PH (65.2 cm) has maximum TSW (45.8 g = 1st rank) but it retains the average kind of SY (26.4 g = 3rd rank) due to the minimum number of SPS (57.8 = 5th rank). Reduction in spike yield of extremely high or low plant stature is since each of both is associated with either less SPS or low TSW. C4 is another class with 2nd largest PH (94.4 cm) and it maintains 4th rank for SY (26.2 g) due to the same reason as it has 2nd maximum TSW (44.5 g) but 2nd minimum SPS (59). C2 and C3 are classes of medium PH (81.1 and 87.3 cm respectively) and they make the actual difference from other classes for maximum SY. C3 represents the mean PH and it just follows the rank of C2 for each of the yield-contributing traits. The second position of C3 for SY indicates the importance of medium plant stature for getting a higher yield potential. But C2 with a slightly shorter stature than average PH gives the most efficient performance. C2 retains 1st rank for SY (27.4 g) due to the average kind of TSW (43.7 g = 3rd rank) and SPS (62.5 = 2nd rank). C2 is the only class that maintains SPS and TSW above the mean values. Otherwise, any class of plant height goes down beyond the mean value either for SPS or TSW. So, maintaining both SPS and TSW on an average range is the best option to enhance yield potential rather than to have one highest and other lowest yield component under limited resources. This is achieved efficiently in this study under the range of PH from 74 to 83 cm represented by C2. This study proves that plants with maximum (C5» 108 cm) or minimum (C5» 65 cm) heights are not suitable due to less spike yield. Only plants with a moderate range of height are showing the best yield potential due to sustainability in TSW and SPS.

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Declaration

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Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

The study was approved by authors.

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Conflict of Interest

There is no conflict of interest among the authors regarding this case study.

Authors Contribution

JAVED HM conducted this research work and all other authors assisted in writeup, data analysis, revision, editing and proof reading equally.

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