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Research Article

# Multivariate Analysis of Selected Wheat Genotypes in Sindh Province

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ABSTRACT

Understanding agro-morphological variability in wheat (*Triticum aestivum* L.) is essential for identifying traits associated with yield potential and for guiding breeding strategies under diverse agro-ecological conditions. This study evaluated 13 wheat cultivars at two contrasting locations, Petaro and Sakrand, to assess variability, trait associations, and principal component contributions. At Petaro, phenological traits exhibited wide variation, with days to heading and maturity showing coefficients of variation of 55% and 130%, respectively, while grain filling period (47-78 days) also varied substantially. Yield components such as grains per spike (24.6-506) and flag leaf area (12.1-79.2 cm$^2$) displayed high variability, whereas grain-related traits (hundred-grain weight, grain dimensions) remained relatively stable. At Sakrand, similar patterns were observed, with days to maturity (120-137) and grain filling period (48-82) showing the widest ranges, while spike length and grain dimensions were comparatively stable. Principal component analysis revealed that the first four components explained 73.18% of the total variability, with peduncle length, flag leaf area, and phenological traits contributing most strongly. Correlation analyses highlighted key associations: at Sakrand, days to maturity and grain filling period correlated positively with peduncle length and plant height, whereas at Petaro, grains per spike strongly correlated with spike length and thousand-grain weight. Negative associations between days to heading and both flag leaf area and hundred-grain weight suggested important trade-offs. Overall, phenological and yield-related traits emerged as primary determinants of variability across environments. These findings provide valuable understandings for selecting wheat genotypes with desirable combinations of traits to enhance yield stability under varying field conditions.

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## Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop of the family Poaceae and serves as a staple food for more than one-third of the global population. It contributes substantially to human diets in the form of chapatti, bread, biscuits, cakes, and other baked products, providing approximately 73% calories, 71% carbohydrates, 6% dietary fiber, 12% water, 2% fats, 12% proteins, and 1.8% minerals. Beyond its nutritional value, wheat straw is widely used as animal fodder to enhance milk yield in cattle and as a raw material for roof covering and plaster reinforcement in rural areas (Debasis and Khurana, 2001).

The domestication of wheat began nearly 10,000 years ago during the Neolithic age, with diploid (AA, einkorn) and tetraploid (AABB, emmer) species first evolving in southeastern Turkey (Feldman, 2001). The emergence of common bread wheat (*T. aestivum*, hexaploid with 42 chromosomes) represented a milestone in global agriculture. However, despite its global importance, wheat cultivation is constrained by low genetic diversity, which limits opportunities for future crop improvement. The narrow genetic base of modern bread wheat is primarily attributed to its origin from restricted hybridization events between *T. dicoccoides* and *T. tauschii*, thereby reducing genetic variation available for breeding (Kimber and Feldman, 2001). Domestication and intensive plant breeding have further eroded this diversity, potentially threatening long-term yield stability and adaptability (Dvorak et al., 1998; Talbert et al., 1998). This highlights the urgent need to evaluate and exploit genetic variation in local and regional germplasm.

Agro-morphological diversity plays a pivotal role in ensuring sustainable wheat production and resilience to environmental stresses. Previous studies have demonstrated significant variation in morphological traits among wheat genotypes, which can be effectively utilized in breeding programs (Mujeeb-Kazi, 1982; Khodadadi et al., 2011; Zarkati et al., 2012). Such diversity supports the development of elite cultivars with enhanced adaptation, yield potential, and stress tolerance (Ajmal et al., 2013).

Sindh province of Pakistan, with its diverse agro-ecological zones, provides contrasting environments for wheat cultivation. Locations such as Sakrand (lower Sindh) and Petaro (central Sindh) differ in soil type, rainfall, and temperature regimes, creating a natural field laboratory for evaluating genetic variability. These agro-climatic factors strongly influence phenotypic expression of key traits such as days to heading, grain filling period, plant height, spike length, and grain weight. Hence, multi-location evaluation of genotypes is essential for identifying stable, high-performing cultivars (Khan et al., 2010). Given the agro-ecological diversity of Sindh, the objectives of the study were to assess the extent of agro-morphological variation among selected wheat genotypes and to determine how multivariate analyses (PCA and correlation) can assist in identifying traits and genotypes valuable for future breeding and sustainable wheat production.

## Materials and Methods

### Experimental locations

The study was conducted at two environmentally distinct locations in Sindh, Pakistan: Wheat Research Institute (WRI), Sakrand, and Petaro. Sowing was carried out at WRI Sakrand on 22 November 2012 and at Petaro on 1 December 2012. These locations differ in their climatic conditions and soil characteristics, providing an opportunity to evaluate the performance and adaptability of wheat accessions under contrasting environments. The detail of wheat germplasm is mentioned in Table 1.

Table 1. Description of wheat varieties.

| Sr. No. | Variety | Parentage |
|---|---|---|
| 1 | Anmol 91 | KVZ/ TRM //PIM /ANA |
| 2 | Skd- 1 | HD-2329 PAU-ACC-3079 |
| 3 | Mehran | VEERY 5'S'CM33027-F-15M-500Y-OM-57B-OY |
| 4 | Abadgar 93 | YAKTANA54 X NORIN 10-BREVOR X SON 64 |
| 5 | TJ 83 | TZPP-PL X 7C |
| 6 | Td 1 | MAI 'S' x NORTEMO 65 x H68 |
| 7 | Moomal 2002 | BUS'S'/4/ TZPP// 1RN46/ CN 067/ 3/PRI-FIK 5644 |
| 8 | Sassui | CHIL/ ALD// PVN/ Yacora-70 |
| 9 | Sarsabz | PI-FROND/PI-MAZOEs |
| 10 | Bhitai | VEE/TRAP#1//SOGHAT-90 |
| 11 | Pavon | VCM x CNO 'S'-7C/KAL-BB |
| 12 | WL-711 | S308-CHR/KAL |
| 13 | Bakhtawar93 | JUP/BJY'S//URES |

**Experimental design and crop husbandry**

The experiment was arranged in a Randomized Complete Block Design (RCBD) with two replications at each location. This design was chosen to minimize environmental variation and ensure reliable comparison among genotypes. Each accession was planted in rows measuring 1.0 m in length with an intra-row spacing of 9 cm. Standard agronomic practices recommended for wheat cultivation in the region, including land preparation, fertilizer application, irrigation, and weed management, were followed uniformly across all plots to minimize management-induced variability.

**Data collection**

Agro-morphological data were recorded on several traits. Days to heading were counted as the number of days from sowing to 50% head emergence; while days to maturity were noted as the number of days from sowing until complete yellowing of the peduncle. The grain filling period was calculated as the difference between days to maturity and days to anthesis. Peduncle length was measured from the base to the uppermost node of the spike, and flag leaf area was estimated by multiplying flag leaf length by its maximum width. Plant height was recorded at maturity from ground level to the tip of the spike, excluding awns, whereas spike length was measured from the base to the tip. Hundred-grain weight was determined using a digital balance, and grain dimensions were measured as the mean length and width of ten randomly selected grains using a foot scale.

**Data analysis**

Data from both locations were subjected to statistical analyses to assess variability and relationships among traits. The following analyses were performed:

**Descriptive statistics**

Mean, range, standard deviation, and coefficient of variation (CV) were calculated for all agro-morphological traits, including days to heading, days to maturity, grain filling period, number of tillers per plant, peduncle length, flag leaf area, plant height, spike length, and hundred-grain weight. These calculations were performed using an online statistical package (www.easycalculation.com/statistics/cumulative-relative-frequency.php

**Frequency distribution**

Frequency distributions of the measured traits were also computed using the same online statistical tool to examine the pattern of variation within the accessions.

**Correlation analysis**

Simple correlation coefficients were calculated using SPSS version 20.0 to determine the degree of association between different agro-morphological traits.

**Principal component analysis (PCA)**

PCA was performed using STATISTICA software to identify the most discriminating traits contributing to variability among accessions. The analysis was conducted following the numerical taxonomic techniques described by Sneath and Sokal (1973).

**Results**

**Variability in agro-morphological traits of wheat cultivars at Petaro**

Agro-morphological traits of wheat cultivars evaluated at Petaro exhibited wide variability (Table 2). Days to heading and maturity averaged 60.9 and 126 days, respectively, with coefficients of variation (CV) of 55% and 130%, indicating substantial diversity in phenology. Grain filling period varied from 47 to 78 days (mean 64.7, CV 75%). Grains per spike showed the widest range (24.6-506) with a mean of 50.9, reflecting high variability (CV 44.3%). Flag leaf area (12.1-79.2 $cm^2$), peduncle length (12-72.5 cm), plant height (35.3-114 cm), and spikes per meter (39-133) also displayed considerable variation with moderate to high CV values (38-87%). Spike length was relatively stable (mean 9.5 cm, CV 9%). Grain-related traits, including hundred-grain weight (mean 4.1 g), ten-grain length (7.39 cm), and ten-grain width (3.39 cm), showed comparatively lower variability (CVs < 8%).

**Variability in agro-morphological traits of wheat cultivars at Sakrand**

Substantial variation was observed among wheat cultivars for all agro-morphological traits. Days to maturity (120-137) and grain filling period (48-82) exhibited the widest ranges, while spike length (5-11.5 cm) and ten-grain dimensions (length: 6.2-8.1 cm; width: 2.9-3.7 cm) showed narrower ranges. Grain number per spike varied considerably (18-67), and 100-grain weight ranged from 0.7 to 9.5 g, indicating pronounced genetic diversity in yield-related traits. High coefficients of variation were recorded for days to maturity (134%) and days to heading (65%), suggesting strong variability, whereas ten-grain width (0.0566%) and length (0.5640%) were relatively stable across genotypes (Table 3).

**PCA of agro-morphological traits in 13 wheat genotypes**

The first four principal components (PC1-PC4) accounted for 73.18% of the total variation, with PC1 contributing 28.64%, PC2 21.98%, PC3 13.45%, and PC4 9.12%. PC1 was mainly associated with peduncle length (-3.51), flag leaf area (1.37), and days to heading (0.61). PC2 was strongly influenced by flag leaf area (-1.86), days to heading (2.73), and days to maturity (1.15). PC3 was characterized by high loadings from hundred grain weight (-0.98) and days to heading (0.73), whereas PC4 was primarily determined by days to maturity (-1.82), flag leaf area (1.68), and plant height (1.14) (Table 4). These results indicate that variation among genotypes is largely explained by phenological and yield-related traits.

Table 2. Basic statistics of agro-morphological traits of wheat cultivars at Petaro.

| Sr. No. | Traits | Mean ± S.E* | Minimum Value | Maximum Value | **CV (%) |
|---|---|---|---|---|---|
| 1 | Days to heading (DH) | 60.9 ± 0.492 | 51 | 71 | 55 |
| 2 | Days to maturity (DM) | 126 ± 0.47 | 116 | 134 | 130 |
| 3 | Grain filling period (GFP) | 64.7 ± 0.78 | 47 | 78 | 75 |
| 4 | Grains/Spike (GS) | 50.854808 ± | 24.6 | 506 | 44.3 |
| 5 | Flag leaf area (cm$^2$) (FLA) | 33.7 ± 1.31 | 12.1 | 79.2 | 43.42 |
| 6 | Peduncle length (cm) (PL) | 37.2± 0.85 | 12 | 72.5 | 38.3 |
| 7 | Plant height (cm) (PH) | 89.5± 1.67 | 35.3 | 114 | 87 |
| 8 | Spike length (cm) (SL) | 9.5 ± 3 | 5 | 13 | 9 |
| 9 | Spikes/meter (SPK/m) | 72.202 ± 2.11 | 39 | 133 | 70 |
| 10 | 100 Grains weight (g) (HGS) | 4.103 ± 0.35 | 2.97 | 493 | 4.35 |
| 11 | Ten grains length (cm) (TGL) | 7.39± 0.04 | 6.3 | 9.2 | 7.6 |
| 12 | Ten grains width (cm) (TGW) | 3.389± 0.02 | 3 | 4 | 3.5 |

S.E. = Slandard Error; C.V. = Coefficient of variation.

Table 3. Descriptive statistics of agro-morphological traits in wheat cultivars evaluated at Sakrand.

| Sr. No. | Trait | Mean ± S.E* | Minimum value | Maximum Value | **C.V (%) |
|---|---|---|---|---|---|
| 1 | Days to heading (DH) | 64.42308±0.51 | 52 | 76 | 65 |
| 2 | Days to maturity (DM) | 129.6635±0.45 | 120 | 137 | 134 |
| 3 | Grain filling period (GFP) | 65.24038±0.68 | 48 | 82 | 69 |
| 4 | Grains/ spike (G/S) | 38.19231±0.95 | 18 | 67 | 38 |
| 5 | Flag leaf area (cm$^2$) (FLA) | 22.31374±0.65 | 5.91 | 51 | 24.939 |
| 6 | Peduncle length (cm) (PL) | 31.68846±0.46 | 21.5 | 49 | 28 |
| 7 | Plant height (cm) (PH) | 67.97981±0.72 | 50 | 84.3 | 72 |
| 8 | Spike length (cm) (SPL) | 8.327885±0.11 | 5 | 11.5 | 8.8 |
| 9 | Spikes /meter (SPK/m) | 60.04808±1.2 | 39 | 94 | 62 |
| 10 | 100 Grains weight (g) (HGS) | 4.203365±0.16 | 0.7 | 9.5 | 6.36 |
| 11 | Ten Grains length (cm) (TGL) | 7.02106±0.03 | 6.2 | 8.1 | 0.5640 |
| 12 | Ten Grains width (cm) (TGW) | 3.242308±0.01 | 2.9 | 3.7 | 0.0566 |

S.E. = Slandard Error; C.V. = Coefficient of variation.

**Correlation coefficients among agro-morphological traits of wheat cultivars at Sakrand**

Days to maturity (DM) showed a strong positive correlation with peduncle length (PL, r = 0.80**) and grain filling period (GFP, r = 0.71**), while GFP was negatively associated with days to heading (DH, r = -0.82**). Plant height (PH) correlated positively with DM (r = 0.63*) and GFP (r = 0.51). Spike length (SPL) exhibited a negative association with total grain length (TGL, r = -0.68*). Hundred grain weight (HGW) was positively related to PH (r = 0.40) and thousand grain weight (TGW, r = 0.47). Overall, GFP and DM emerged as key traits influencing yield-related parameters (Table 5).

**Correlation coefficients among agro-morphological traits of wheat cultivars at Petaro**

Days to heading (DH) showed significant negative correlations with hundred grain weight (HGW; r = -0.65*) and with flag leaf area (FLA; r = -0.70**). Plant height (PH) was positively associated with peduncle length (PL; r = 0.64*) and HGW (r = 0.58), while grains per spike (GS) correlated strongly and positively with spike length (SPL; r = 0.78**) and thousand grain weight (TGW; r = 0.68*). Grain filling period (GFP) was positively related to days to maturity (DM; r = 0.70**). In contrast, several negative associations were observed, including between GS and GFP (r = -0.49) and between TGW and DM (r = -0.35) (Table 6).

Table 4. Principal component analysis of agro-morphological traits in 13 wheat genotypes.

| PC | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Eigenvalue | 3.43644 | 2.63708 | 1.61362 | 1.09462 |
| % variance | 28.637 | 21.976 | 13.447 | 9.1218 |
| Cumulative variance% | 28.637 | 50.613 | 64.06 | 73.1818 |
| Eigen vectors | | | | |
| DH | 0.61237 | 2.7261 | 0.73496 | -1.5901 |
| FLA | 1.3688 | -1.8584 | -0.26779 | 1.6765 |
| PL | -3.5117 | -1.2966 | 0.37841 | 0.42603 |
| DM | -0.49405 | 1.149 | -0.47978 | -1.819 |
| GFP | 0.6934 | -1.4667 | -0.26675 | -1.04 |
| PH | -1.0889 | 0.59795 | 0.14422 | 1.142 |
| SPL | -0.081796 | -0.94944 | -0.07636 | -1.041 |
| Spikes/m | 0.018497 | 0.26078 | -0.00353 | 0.35995 |
| G/S | -0.015699 | 0.27688 | 0.27128 | -0.51511 |
| HGW | -0.051292 | 0.18332 | -0.98405 | 0.12674 |
| TGL | 0.040341 | -0.14413 | -0.02384 | 0.04284 |
| TGW | -0.080629 | 0.000888 | 0.026901 | 0.014693 |

DH = Days to heading, FLA = Flag leaf area, PL = Peduncle length, DM = Days to maturity, GFP = Grain filling period, PH = Plant Height, SPL = Spike Length,Spk/m = Spikes / meter, G/S = Grains per Spike, HGW = Hundred Grains Weight.

Table 5. Correlation among agro-morphological traits of wheat cultivars at Sakrand.

| | DH | FLA | PL | DM | GFP | PH | SPL | SPM | GS | HGW | TGL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FLA | -0.35 | | | | | | | | | | |
| PL | -0.26 | -0.07 | | | | | | | | | |
| DM | -0.17 | 0.06 | 0.80** | | | | | | | | |
| GFP | -0.82** | 0.28 | 0.65* | 0.71** | | | | | | | |
| PH | -0.19 | 0.11 | 0.35 | 0.63* | 0.51 | | | | | | |
| SPL | -0.53 | 0.15 | -0.18 | 0.01 | 0.38 | 0.15 | | | | | |
| SPM | 0.27 | -0.09 | 0.26 | 0.31 | -0.01 | -0.23 | -0.07 | | | | |
| GS | -0.18 | -0.22 | 0.15 | 0.03 | 0.15 | 0.15 | 0.11 | -0.49 | | | |
| HGW | 0.39 | 0.08 | -0.06 | 0.23 | -0.15 | 0.40 | 0.21 | 0.01 | -0.05 | | |
| TGL | 0.14 | -0.18 | -0.04 | -0.21 | -0.22 | -0.19 | -0.68* | -0.23 | -0.11 | -0.38 | |
| TGW | 0.29 | 0.28 | -0.20 | -0.29 | -0.38 | -0.02 | 0.09 | -0.18 | 0.32 | 0.47 | -0.27 |

FLA = Flag leaf area, PL = Peduncle length, DM = Days to maturity, GFP = Grain filling period, PH = Plant Height, SPL = Spike Length, G/S = Grains per Spike, HGW = Hundred Grains Weight.

The principal component biplot of PC1 and PC2 revealed distinct associations among the studied traits. Traits such as plant length (PL), days to maturity (DM), grain filling period (GFP), and number of spikelets per main spike (Spm) showed positive associations, as indicated by acute angles between their vectors. Similarly, flag leaf area (FLA), days to heading (DH), and grain length (GL) clustered together, reflecting mutual correlations. In contrast, vectors forming obtuse angles, such as between PL/DM/GFP and DH/FLA, indicated negative associations. Traits like thousand grain weight (TGW), grain size (GS), and spike length (SPL) were closely aligned, suggesting positive interrelationships (Figure 1). Overall, the biplot highlights key trait groupings and trade-offs contributing to phenotypic diversity among the wheat genotypes.

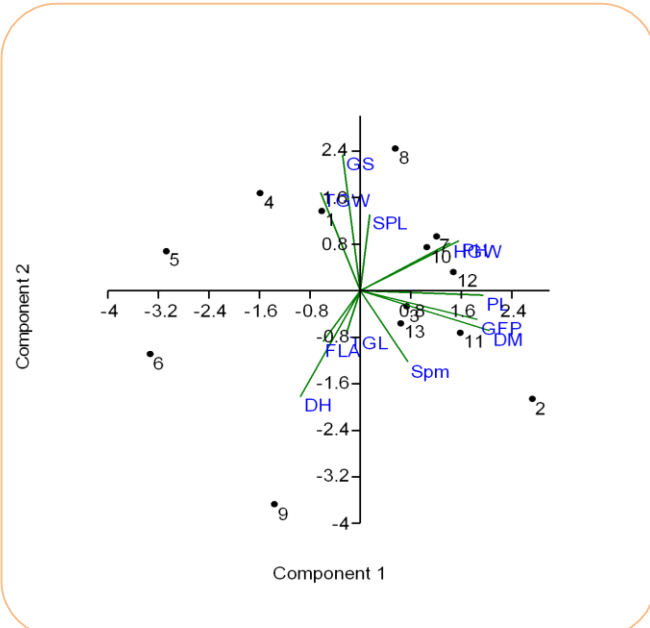


Figure 1. Principal component biplot of PC1 and PC2 based on trait means. Trait vectors with angles less than 90° indicate positive associations, while those greater than 90° indicate negative associations.

Figure 2 shows the principal component biplot of PC1 and PC3 based on trait means. Traits positioned with acute angles (less than 90°) exhibit positive correlations, whereas those with obtuse angles (greater than 90°) show negative correlations. Days to heading (DH), thousand-grain weight (TGW), total grains per spikelet (TGGL), and grain per spikelet length (GSPL) are positively associated, while spikelet per main spike (Spm) shows a negative association with them. Plant height (PH), days to maturity (DM), and hundred-grain weight (HGW) cluster together, indicating positive correlations. The distribution of traits along PC1 and PC3 highlights their varying contributions to overall variability among genotypes.

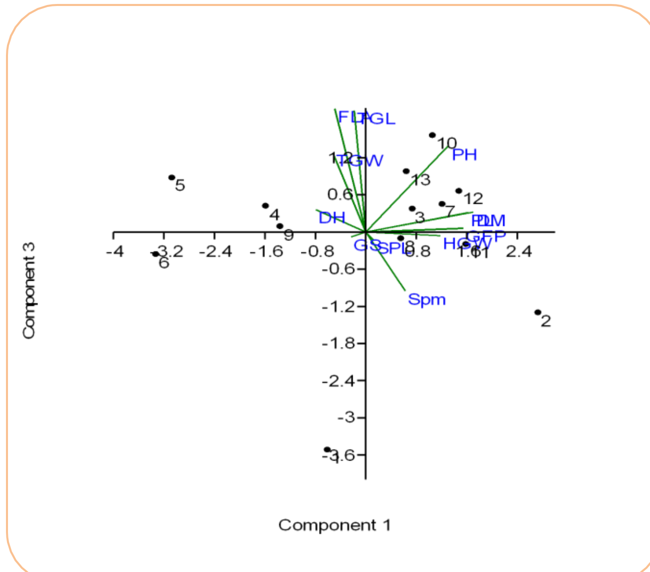


Figure 2. Principal component biplot of PC1 and PC3 based on trait means. Trait vectors with angles less than 90° indicate positive correlations, while those with angles greater than 90° indicate negative correlations.

Table 6. Correlation among agro-morphological traits of wheat cultivars at Petaro.

| | DH | FLA | PL | DM | GFP | PH | SPL | SPM | GS | HGW | TGL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FLA | 0.43 | | | | | | | | | | |
| PL | -0.28 | 0.00 | | | | | | | | | |
| DM | 0.03 | 0.06 | 0.27 | | | | | | | | |
| GFP | -0.04 | 0.17 | 0.10 | 0.70** | | | | | | | |
| PH | -0.49 | -0.07 | 0.64* | 0.12 | -0.10 | | | | | | |
| SPL | -0.09 | -0.31 | -0.20 | -0.33 | -0.44 | 0.30 | | | | | |
| SPM | -0.07 | -0.22 | -0.03 | 0.30 | 0.46 | 0.03 | -0.15 | | | | |
| GS | -0.25 | 0.01 | 0.06 | -0.47 | -0.49 | 0.54 | 0.78** | -0.40 | | | |
| HGW | -0.65* | -0.70** | 0.43 | 0.37 | 0.09 | 0.58 | 0.21 | 0.42 | 0.02 | | |
| TGL | 0.10 | 0.41 | 0.26 | -0.01 | -0.25 | 0.23 | -0.38 | -0.10 | -0.10 | -0.08 | |
| TGW | -0.36 | 0.27 | -0.13 | -0.35 | -0.26 | 0.42 | 0.37 | -0.32 | 0.68* | -0.17 | 0.13 |

FLA = Flag leaf area, PL = Peduncle length, DM = Days to maturity, GFP = Grain filling period, PH = Plant Height, SPL = Spike Length, G/S = Grains per Spike, HGW = Hundred Grains Weight.

## Discussion

The significant variability observed in agro-morphological traits among wheat cultivars at Petaro and Sakrand highlights a substantial genetic diversity within the evaluated germplasm. This diversity is a crucial foundation for breeding programs aiming to develop cultivars adapted to specific local conditions. The high coefficients of variation for phenological traits like days to heading and maturity, as well as for components such as grains per spike, suggest that there is considerable scope for selecting genotypes with optimal combinations of these characteristics (Yang et al., 2016). Notably, traits related to grain dimensions (e.g., ten-grain length and width) exhibited lower variability, indicating they may be under more stable genetic control or stronger selection pressure in past breeding efforts (Zhao et al., 2025).

The correlation analyses reveal critical interrelationships among traits that define yield architecture. The strong positive correlation between grains per spike and spike length at Petaro is consistent with findings that modern wheat varieties often achieve higher yields through increased grain number per spikelet (Zhou et al., 2021). Furthermore, the positive association between plant height and both peduncle length and hundred-grain weight highlights the complex role of plant structure in resource allocation towards grain filling. This aligns with research showing that the peduncle, as a key component of plant height, is critical for transporting assimilates to the developing grain (Liu et al., 2023). The negative correlation between days to heading and hundred-grain weight at Petaro suggests a potential trade-off between the vegetative phase duration and the capacity for grain filling, a balance that breeding must carefully manage (Yang et al., 2016).

The Principal Component Analysis confirms that the majority of genetic variation is explained by a combination of phenological and yield-related traits. The high loadings of peduncle length and flag leaf area on the first two principal components emphasize their importance as determinants of plant architecture. The flag leaf is a major source of photosynthates during grain filling, contributing 45-58% of the plant's photosynthate, and its area is a key determinant of yield potential (Yang et al., 2016; Wang et al., 2022). Therefore, selecting for optimal flag leaf morphology is essential for improving photosynthetic efficiency and grain yield.

The differences in trait correlations between the two locations, particularly the contrasting relationships involving the grain filling period (GFP), likely reflect the significant interaction between genotype and environment (G×E). Environmental factors such as water availability and temperature can profoundly influence grain-filling dynamics (Yang et al., 2016, Liang et al., 2024). For instance, under drought stress, cultivars may adjust their grain-filling strategies, sometimes shortening the duration but increasing the rate to ensure maturity (Liang et al., 2024; Zhang et al., 2024). This is supported by broader studies showing that grain-filling characteristics are a major focus of modern breeding, with newer cultivars often achieving higher kernel weight through modified filling rates and durations (Zhang et al., 2024; Zhao et al., 2025). The strong positive correlation between GFP and days to maturity at both sites, however, underscores that extending the reproductive phase is a fundamental mechanism for lengthening the grain filling period, which can be critical for achieving higher yields provided that environmental stresses do not terminate the cycle prematurely (Liang et al., 2024).

## Conclusion

The evaluation of wheat cultivars at Petaro and Sakrand revealed substantial agro-morphological variability, particularly in phenological traits such as days to heading, days to maturity, and grain filling period, which exhibited wide ranges and high coefficients of variation. Yield-related traits including grains per spike, peduncle length, flag leaf area, and plant height also showed considerable diversity, while grain dimensions and hundred-grain weight were relatively stable, suggesting stronger genetic control. Principal Component Analysis confirmed that phenological and yield-related traits, especially flag leaf area, peduncle length, and days to maturity, accounted for most of the observed variation. Correlation analyses further highlighted the critical roles of peduncle length, grain filling period, and plant height in determining yield potential, while trade-offs were evident between early heading and grain weight.

## Recommendations

Based on these findings, it is recommended that breeding programs prioritize the selection of genotypes with longer grain filling periods, optimal flag leaf morphology, and strong assimilate partitioning capacity through peduncle length and plant stature. Stability in grain size traits should be exploited to ensure consistent kernel quality, while the identified correlations provide useful selection criteria for indirect improvement of yield. Multi-environment testing should be conducted to validate genotype × environment interactions, and promising genotypes with favorable trait combinations should be advanced for further breeding and adaptability studies.

## Authors' Contributions

ARM conceived and designed the study, conducted data collection, performed statistical analysis, and prepared the initial draft of the manuscript; ARJ assisted in experimental design, supervised field evaluations, and contributed to data interpretation; MSS provided technical guidance, reviewed literature, and contributed to manuscript structuring and critical revisions; AST assisted in field experimentation, data management, and preparation of tables and figures; FAM contributed to statistical analysis, editing, proofreading, and finalization of the manuscript for submission.

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## Conflict of Interest

The authors declare no conflict of interest.

## Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

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