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## COMPARATIVE PERFORMANCE OF SINGLE AND THREE-WAY CROSS MAIZE HYBRIDS DEVELOPED FROM TROPICAL AND SUB-TROPICAL INBRED LINES FOR YIELD TRAITS

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### ABSTRACT

Maize (*Zea mays L.*) is a strategic crop in Pakistan. However, national outputs have not reached the global average, as the available hybrids lack flexibility. Local studies on maize have given limited attention to three-way crosses. Meanwhile, research on single-cross hybrids has been more prevalent. However, it has not focused firmly on exploiting three-way combinations for yield potential and stability across diverse environments. The present investigation aimed to compare the performance of single- and three-way cross maize hybrids derived from tropical and subtropical inbred lines, to identify high-yielding and stable cultivars. A total of 20 hybrids, including nine single crosses, eight three-way crosses, and three commercial checks, were evaluated during the summer of 2019 at two contrasting sites in Khyber Pakhtunkhwa using a randomised complete block design with three replications. The analysis revealed highly significant differences ( $p < 0.01$ ) among genotypes, along with substantial genotype-by-environment interactions, highlighting the influence of environmental variation on hybrid performance. Among the hybrids, PSWH-201905, PSWH-201911, PSWH-201912, and PSWH-201913 consistently outperformed others in grain yield and yield-related traits, though earliness traits showed a negative association with yield. Furthermore, high estimates of heritability and genetic gain confirmed the presence of sufficient genetic variability for selection. Thus, the findings suggest that three-way crosses can offer desirable combinations of yield and stability, help address an existing research gap, and provide promising alternatives for maize production in Pakistan's variable agro-climatic conditions.

**Keywords:** *Maize hybrids, Genotype × environment interaction, Grain yield, Heritability, Breeding potential*

## Introduction

Maize (*Zea mays L.*) is one of the most valuable cereal crops in the world. It is at the centre of food production, feeding, and industry. Maize is a C4 plant that belongs to the family Poaceae, exhibiting high photosynthetic efficiency, broad adaptability, and high yield potential (Erenstein *et al.*, 2022). It is planted in tropical, subtropical, and temperate zones. Therefore, it is one of the most adaptable crops in the world. Maize is the leading cereal in global production (more than wheat and rice). It also plays a vital role in food security, animal feed chains, and the industry as a source of starch, syrup, oil, and ethanol (Kaul *et al.*, 2019). According to Monday Adiaha *et al.* (2021), maize is a strategic crop due to its multivariate significance in sustaining human populations and promoting economic development in both developed and developing nations.

In Pakistan, maize is grown on approximately 1.3 million hectares, yielding around 6.3 million tonnes/year, with an average grain yield of 4,787 kg/ha (PARC, 2025). This is a significant contribution to national agriculture, but maize productivity in the country remains significantly lower than the global average. The yield gap represents a convergence of factors that may include the production of poorly adapted varieties, inefficient agronomic practices, erratic rainfall patterns, limited irrigation, and biotic stresses such as insect pests and diseases. Pieter *et al.* (2023) found that farmers typically use cultivars that fail to perform consistently across various environments, leading to yield volatility and income loss. It is causing yield gaps of nearly 20–24% ( $\approx 13$ – $18$  t/ha) and significant income instability. Such spatial and temporal variability—ranging from 8 to 11 t/ha among fields—highlights the risk of not matching cultivars to local conditions (Pieter *et al.*, 2023).

As Yue *et al.* (2025) explain, yield in maize, like that in most cereals, is a quantitative trait that depends on several genetic and environmental factors. Genotype  $\times$  environment interaction (GEI) is one of the most significant challenges in breeding to improve yield. Conversely, Laban Konaté *et al.* (2023) explain that hybrids that perform better in one environment also do not perform well in another, making it challenging to determine generalized and reliable cultivars. Supriadi *et al.* (2024) explain that it is for this reason that testing hybrids of maize under various environments is essential, not only to define the level of GEI, but also to identify cultivars whose performance is predictable.

Knowledge of the nature and magnitude of the genetic variation governing the inheritance of quantitative traits, such as yield and its components, is essential for assessing genetic improvement in maize. Highly heritable and genetically advanced traits offer opportunities to be effectively selected and accurately developed in subsequent generations (Dragov *et al.*, 2022). The yield components primarily analyzed in the study by Long *et al.* (2024) include kernel rows per ear, kernels per row, and the weight of kernels themselves, which are key contributing factors to grain yield and commonly serve as breeding criteria in maize breeding programs. By estimating the genetic parameters in

experimental material, breeders gain a deeper understanding of trait inheritance and make informed choices regarding the hybrids they breed or cross.

Despite the increase in hybrid maize technology in Pakistan, commercially available hybrids have been developed based on a limited number of genetic circumstances. Consequently, they become less adaptive to various settings, as described in the research of Ali *et al.* (2020). Additionally, there is a lack of research on the comparative analysis of single and triple cross hybrids produced using tropical and subtropical inbred lines. Similar to the case outlined in Sorsa *et al.*'s (2023) study, single crosses, which are uniform genetically, tend to exhibit elevated heterosis but lack general adaptability. In contrast, Dhakal *et al.* (2022) have explicitly compared single- versus three-way maize hybrids across multi-location, multi-year trials with formal  $G \times E$  and stability analyses. Where three-way crosses were included, the scope was narrow, so evidence on their practical superiority under farmer-relevant conditions remains limited. Their comparative performance in various environments is thus imperative for designing breeding plans as well as for prescribing hybrids that can accommodate the diverse production requirements of Pakistani farmers. Therefore, this study is essential as it may help discover hybrids that are both high-yielding and stable, as well as early flowering, which are crucial in Pakistan's unpredictable agro-climatic conditions. Amsal Tarekegne *et al.* (2024) categorized early-maturing hybrids as those that allow farmers to combine maize with other crops, optimizing land use, and responding to terminal drought stress; stable hybrids as those that provide reliability in production under changing environmental conditions. This study bridges the knowledge gap by providing scientific evidence of the performance of experimental hybrids across contrasting sites.

The aim of the current research was thus to compare the performance of single-cross maize hybrids versus three-way cross maize hybrids developed between tropical and sub-tropical inbred lines in terms of yield and yield-related characteristics. The primary goal was to determine their genotypic potential and plasticity in two different environments in Khyber Pakhtunkhwa. The results are likely to inform future breeding initiatives aimed at producing better hybrids, which can contribute to improved productivity, sustainable agriculture, and food security in Pakistan.

## **Materials and methods**

### **Breeding material and procedure**

During the 2019 summer season, 20 maize hybrids were evaluated with white kernels. Among these were 17 experimental crosses (nine single-cross and eight three-way cross combinations) along with three commercial checks—Babar, Jalal, and CS-240 (Table 1). The trials followed a randomized complete block design (RCBD) with three replications, carried out at two different sites: the Cereal Crops Research Institute (CCRI) in Pirsabak-Nowshera and the University of Agriculture, Peshawar

(UAP), both located in Khyber Pakhtunkhwa, Pakistan. The CCRI at Pirsabak supplied the breeding material used in this study.

**Table 1. Maize experimental hybrids and check cultivars were used in the study.**

S.No.	Genotype Code	Genotype Details	Source
1	PSWH-201901	Exp. Single Cross Hybrid	CCRI
2	PSWH-201902	-do-	-do-
3	PSWH-201903	-do-	-do-
4	PSWH-201911	-do-	-do-
5	PSWH-201912	-do-	-do-
6	PSWH-201913	-do-	-do-
7	PSWH-201914	-do-	-do-
8	PSWH-201915	-do-	-do-
9	PSWH-201917	-do-	-do-
10	PSWH-201904	Exp. Three-Way Cross Hybrid	-do-
11	PSWH-201905	-do-	-do-
12	PSWH-201906	-do-	-do-
13	PSWH-201907	-do-	-do-
14	PSWH-201908	-do-	-do-
15	PSWH-201909	-do-	-do-
16	PSWH-201910	-do-	-do-
17	PSWH-201916	-do-	-do-
<b>Check cultivars</b>			
18	Babar	Comm. Double Cross Hybrid	-do-
19	Jalal	Comm. Open Pollinated Variety (OPV)	-do-
20	CS-240	Comm. National Single Cross Hybrid	Petal Seed Comp.

PSWH: Pirsabak White Hybrid, Exp.: Experimental, Comm.: Commercial, CCRI: CCRI, Pirsabak – Nowshera  
 Each experimental plot measured five meters in length and consisted of two plant rows, spaced 25 cm within rows and 75 cm between rows. Fertiliser was applied at a rate of 170:70 NP kg ha<sup>-1</sup>. At land preparation and sowing, the full dose of phosphorus (as P<sub>2</sub>O<sub>5</sub>) and half of the nitrogen were incorporated using DAP and urea, respectively. The remaining nitrogen was top-dressed as urea approximately five weeks after crop emergence, just before earthing up. Weed management involved the application of Primextra Gold (2500 ml ha<sup>-1</sup>), while any subsequent weed growth was controlled through earthing-up operations around six weeks after emergence. For insect control, seeds were treated with Confidor before sowing, and Furadon granules were applied to the whorls approximately

one month after planting. Irrigation was provided according to crop requirements, with watering stopped one week before physiological maturity.

### Data recorded

Biological yield was determined by harvesting all maize plants within each subplot. After sun-drying, the harvested bundles were weighed separately for every genotype, and the data were converted into kilograms per hectare. To assess cob traits, ten ears were randomly chosen from the harvest. Their diameters were measured in centimetres using a Vernier calliper, while ear length was recorded with a ruler from base to tip. For yield components, the number of grain rows per cob was counted on the selected ears, and the average number of grains per row was calculated from the same sample. Fresh cob weight was also recorded at harvest, using an electric balance on ten randomly chosen plants per treatment, and the results were averaged. Finally, from each entry, a sample of 200 kernels was taken from the threshed seed and weighed in grams with an electric balance.

### Grain yield (kg ha<sup>-1</sup>)

Grain yield (kg ha<sup>-1</sup>) for each treatment was calculated by using the following formula:

$$\text{Grain yield (kg ha}^{-1}\text{)} = \frac{(100 - \text{MC}) \times \text{FEW} \times \text{Shelling coefficient} \times 10,000}{(100 - 15) \times \text{Plot area}}$$

Where,

MC = Moisture content (%) in grains at harvest

FEW = Fresh ear weight (kg) at harvest

Shelling coefficient = 0.80

1 hectare = 10,000 m<sup>2</sup>

100 - 15 = Required moisture for storage

Area to be harvested (plot size) = 7.5 m<sup>2</sup>

### Harvest index (%)

The harvest index was calculated using the formula below (Tollenaar *et al.*, 2004; Lee *et al.*, 2005).

$$\text{Harvest Index (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

### Statistical analyses

#### Analysis of variance

The collected data for all measured traits were subjected to genotype × environment interaction analysis of variance (ANOVA) using the procedure outlined by Gomez and Gomez (1984) (Table 2). This analysis tested the null hypothesis that there were no significant differences among the

experimental maize hybrids and check cultivars (G), the environments (E), or their interactions (GEI). Once considerable variation was detected for these sources of variation, mean comparisons were performed using the least significant difference (LSD) test at the 5% probability level.

**Table 2. ANOVA for genotype by environment interaction studies.**

Source of Variation	Degree of Freedom (d.f.)	Mean Squares (MS)	F calculated Values
Locations / Environments (L/E)	L-1	LMS	LMS/RMS
Reps. with in location (R)	L(R-1)	RMS	-
Genotypes (G)	G-1	GMS	GMS/EMS
G × L interaction (GEI)	(G-1) (L-1)	G × LMS	L × GMS/EMS
Pooled Error	L (R-1) (G-1)	EMS	-
Total	LRG-1	-	-

#### IV. RESULTS AND DISCUSSION

##### Pooled analysis of variance

This study evaluated the genetic potential of seventeen experimental maize hybrids (single and three-way crosses) alongside three check cultivars—Babar, Jalal, and CS-240—focusing on earliness, morphological traits, and yield performance at two sites: the University of Agriculture, Peshawar (UAP), and the Cereal Crops Research Institute (CCRI), Pirsabak, Nowshera, in Khyber Pakhtunkhwa. The combined analysis of variance revealed highly significant differences ( $p \leq 0.01$ ) among genotypes for most traits, except for ear length, which was nonsignificant. Biological yield and 200-kernel weight also showed significant differences, though at the 5% level (Table 3). Environmental effects were significant ( $p \leq 0.01$ ) for nearly all parameters, except kernel rows per ear and harvest index. Previous research supports these findings. Kara *et al.* (2020) reported strong genotypic and environmental influences on earliness and yield traits, while Yue *et al.* (2025) noted that genotype × location and genotype × location × planting time interactions were mainly nonsignificant. Similarly, Bhadmus *et al.* (2021) observed significant genotype-by-environment ( $G \times E$ ) interaction effects for earliness traits and grain yield. Katsenios *et al.* (2021) highlighted pronounced  $G \times E$  interactions in characteristics such as earliness, ears per square meter, and grain yield. Ali *et al.* (2018) further demonstrated significant  $G \times E$  effects on earliness, cob length, 1000-kernel weight, and grain yield in maize composites. Moreover, substantial cycle × year × location interactions were also documented for specific yield-related parameters, particularly kernel rows per ear.

##### Biological yield

The present analysis confirmed genotype × environment interactions, particularly among single-cross hybrids, indicating that variations in biological yield and yield-related traits were primarily influenced

by differences in the genetic makeup of hybrids across environments. Biological yield among genotypes ranged from 12,339 to 16,292 kg ha<sup>-1</sup>, while genotype × environment combinations varied between 7,157 and 19,651 kg ha<sup>-1</sup> (Table 5). Based on genotype means, the F1 hybrid PSWH-201911 recorded the highest biological yield (16,292 kg ha<sup>-1</sup>), performing on par with eight other hybrids, including PSWH-201909, PSWH-201912, PSWH-201903, PSWH-201905, PSWH-201917, PSWH-201914, and PSWH-201904. In contrast, PSWH-201906 produced the lowest yield (12,339 kg ha<sup>-1</sup>). Several other hybrids—PSWH-201916, PSWH-201902, PSWH-201913, PSWH-201907, PSWH-201910, PSWH-201915—along with the check cultivars Jalal and Babar, showed intermediate performance, with yields ranging between approximately 12,426 and 15,000 kg ha<sup>-1</sup>.

Across environments, the highest average yield was recorded at CCRI (17,925 kg ha<sup>-1</sup>), while the lowest was observed at UAP (10,172 kg ha<sup>-1</sup>). In the genotype × environment combinations, PSWH-201911 again achieved the maximum yield in the CCRI environment (19,651 kg ha<sup>-1</sup>). Several other hybrids—PSWH-201905, PSWH-201903, PSWH-201912, PSWH-201909, PSWH-201902, and PSWH-201915—also produced high yields under this location, ranging between 18,400 and 18,600 kg ha<sup>-1</sup>. The lowest performance was noted for PSWH-201902 grown at UAP (7,157 kg ha<sup>-1</sup>). Overall, PSWH-201911 consistently ranked as the best-performing genotype, both in mean yield across environments and in genotype × environment interactions.

### **Fresh ear weight**

For fresh ear weight, genotype means varied between 5.51 and 7.63 kg per plot, while the genotype × environment interaction values ranged more widely, from 2.70 to 10.33 kg per plot (Table 6). Among the genotypes, the F1 hybrid PSHW-201911 recorded the highest mean fresh ear weight (7.63 kg plot<sup>-1</sup>). This was closely followed by PSHW-201905, PSHW-201909, PSHW-201912, PSHW-201917, and the check cultivar CS-240, which produced mean values ranging from 7.30 to 7.58 kg plot<sup>-1</sup>. In contrast, PSHW-201902 (5.51 kg plot<sup>-1</sup>) and the check cultivar Babar (5.58 kg plot<sup>-1</sup>) registered the lowest fresh ear weights.

Environmental effects were also pronounced: genotypes grown at CCRI averaged higher fresh ear weight (8.70 kg per plot<sup>-1</sup>), whereas those at UAP produced lower values (4.63 kg per plot<sup>-1</sup>). Similar trends were noted by Berhanu Bilate Daemo *et al.* (2024), who reported that maize genotypes responded differently under varying conditions due to strong genotype × environment interactions influencing fresh ear weight and yield attributes. Likewise, Alam *et al.* (2022) demonstrated significant variation in ear weight across multiple ecological zones, confirming the influence of both genotype and environmental interaction.

In terms of genotype × environment combinations, PSHW-201905 achieved the maximum fresh ear weight at CCRI (10.33 kg plot<sup>-1</sup>), performing statistically on par with several other hybrids, including

PSHW-201917, PSHW-201912, PSHW-201909, PSHW-201911, PSHW-201904, PSHW-201915, and PSHW-201907. Conversely, the lowest performance was recorded for PSHW-201902 at UAP (2.70 kg plot<sup>-1</sup>), followed by PSHW-201915 (3.63 kg plot<sup>-1</sup>), PSHW-201917 (4.20 kg plot<sup>-1</sup>), and PSHW-201916 (4.26 kg plot<sup>-1</sup>).

### **Ear length**

Consistent with the present findings, earlier studies have also reported significant differences among genotypes, environments, and their interactions for ear length and related ear traits in maize. For example, Baye *et al.* (2011) observed considerable variation in maize populations across diverse environments, with significant genotype, genotype × location, and genotype × location × year effects on ear characteristics. Similarly, recurrent selection has been shown to improve cob length, number of rows per cob, 1000-grain weight, and grain yield in different maize genotypes.

In this study, ear length ranged from 16.21 to 18.63 cm among genotypes, and from 15.17 to 21.33 cm across genotype × environment interactions (Table 7). The F1 hybrid PSWH-201912 recorded the maximum average ear length (18.63 cm), closely followed by PSWH-201917, PSWH-201915, PSWH-201901, and the check cultivar Babar, with values ranging from 17.58 to 18.05 cm. The shortest ears were observed in PSWH-201909 (16.21 cm), which was statistically similar to PSWH-201906, PSWH-201905, PSWH-201907, PSWH-201908, PSWH-201914, PSWH-201910, and the check cultivar Jalal (16.46–16.95 cm).

Environmental means further revealed that genotypes produced longer ears at CCRI (18.01 cm) compared to UAP (16.33 cm). Within genotype × environment interactions, PSWH-201912 attained the maximum ear length at CCRI (21.33 cm). Comparable values were also recorded for PSWH-201901, PSWH-201917, PSWH-201915, PSWH-201904, PSWH-201907, PSWH-201902, and the check cultivar Babar, which ranged from 18.33 to 19.23 cm under the exact location. Conversely, the lowest ear length was observed for PSWH-201907 at UAP (15.17 cm), followed by PSWH-201914, PSWH-201905, PSWH-201904, PSWH-201910, PSWH-201902, and the check cultivars Babar and Jalal, with values ranging from 15.53 to 16.13 cm.

### **Ear diameter**

Ear diameter among genotypes ranged from 4.38 to 4.80 cm, while genotype × environment interaction values varied between 4.26 and 5.13 cm (Table 8). The F1 hybrid PSWH-201915 recorded the largest mean ear diameter (4.80 cm), followed by PSWH-201902, PSWH-201914, PSWH-201911, PSWH-201904, PSWH-201909, PSWH-201907, and the check cultivar Babar, which produced values around 4.56 cm. In contrast, PSWH-201903 (4.38 cm) exhibited the smallest diameter, similar to PSWH-201906, PSWH-201913, PSWH-201916, PSWH-201908, PSWH-201910, and the check cultivar Jalal, with values ranging from 4.38 to 4.43 cm.

Environmental influence was also evident, with the highest average ear diameter recorded at CCRI (4.65 cm) and the lowest at UAP (4.45 cm). Under genotype  $\times$  environment interactions, PSWH-201915 achieved the maximum ear diameter at CCRI (5.13 cm), comparable to those of PSWH-201902 (5.00 cm), PSWH-201911 (4.96 cm), PSWH-201904 (4.93 cm), and PSWH-201914 (4.93 cm). Conversely, PSWH-201903 exhibited the minimum ear diameter at CCRI (4.26 cm), which was statistically similar to that of PSWH-201913, PSWH-201905, PSWH-201916, and PSWH-201910, all of which produced values between 4.33 and 4.36 cm when grown at UAP.

Overall, both genotype means and genotype  $\times$  environment analysis confirmed PSWH-201915 as the top performer in terms of ear diameter. These findings align with those of Gao *et al.* (2025), who reported that a large proportion of variation in ear diameter is explained by environmental effects, emphasizing the importance of selection across diverse environments. The presence of significant genetic variability further indicates considerable potential for improvement through breeding and selection.

#### **Kernel rows per ear**

Kernel rows per ear varied among genotypes, ranging from 12.50 to 15.50, while genotype  $\times$  environment interaction values ranged from 12.00 to 16.67 (Table 9). The F1 hybrid PSWH-201913 recorded the highest mean number of rows (15.50), closely followed by PSWH-201907, PSWH-201916, PSWH-201912, PSWH-201917, and PSWH-201903, with values ranging from 14.16 to 15.33. The lowest value was observed in PSWH-201905 (12.50), which was statistically similar to PSWH-201904, PSWH-201915, PSWH-201908, PSWH-201910, PSWH-201914, PSWH-201902, PSWH-201911, and the check cultivar Babar.

Environmental means showed slight variation, with CCRI producing the highest number of kernel rows per ear (13.91) compared to UAP (13.81). In genotype  $\times$  environment interactions, PSWH-201913 achieved the maximum value when grown at CCRI (16.67), performing similarly to PSWH-201916 (16.00), PSWH-201912 (15.33), and PSWH-201917 (15.00) at the same site, as well as PSWH-201902 (15.00) at UAP. The minimum number of rows was recorded in PSWH-201904 and PSWH-201915 (12.00) at UAP, followed by PSWH-201902, PSWH-201905, PSWH-201910, and the check cultivar Babar, all with 12.33 rows per ear.

#### **Kernels per row**

The number of kernels per row among genotypes ranged from 33.16 to 41.83, while genotype  $\times$  environment interaction values extended from 29.00 to 47.33 (Table 10). The F1 hybrid PSWH-201908 recorded the maximum kernel count per row (41.83), followed by PSWH-201909, PSWH-201905, PSWH-201914, PSWH-201912, and PSWH-201917, which produced 39.00 to 40.33 kernels

per row. On the lower end, PSWH-201902 (33.16) and PSWH-201913 and PSWH-201916 (33.16–35.00) exhibited the smallest values, along with the check cultivar Babar.

Environmental means revealed that UAP produced the highest number of kernels per row (39.61), whereas CCRI had the lowest (35.53). Within genotype  $\times$  environment interactions, PSWH-201912 displayed the maximum value (47.33), while PSWH-201908 (44.67), PSWH-201914 (44.00), PSWH-201903 (42.33), PSWH-201904 (41.66), and PSWH-201909 (41.00) also performed well. In contrast, PSWH-201903 produced the lowest kernel count per row at CCRI (29.00). Similar to PSWH-201916, PSWH-201902, PSWH-201912, PSWH-201913, and PSWH-201906, which ranged from 29.33 to 33.00. Overall, significant variation was observed among maize genotypes for kernels per row and related yield traits, confirming the strong influence of both genetic factors and environmental conditions on yield performance.

### **200-kernel weight**

The 200-kernel weight among genotypes ranged from 71.63 to 87.40 g, while genotype  $\times$  environment interaction values extended from 66.73 to 98.50 g (Table 11). Based on genotype means, the F1 hybrid PSWH-201915 recorded the maximum value (87.40 g), followed closely by PSWH-201905 (86.41 g), PSWH-201908 (86.40 g), PSWH-201913 (85.95 g), and PSWH-201917 (84.76 g). In contrast, PSWH-201902 exhibited the lowest 200-kernel weight (71.63 g), which was statistically similar to PSWH-201911 and PSWH-201912 (72.35–73.98 g). Environmental averages revealed that genotypes attained the highest 200-kernel weight at CCRI (84.47 g), whereas UAP recorded the lowest (75.44 g). Within genotype  $\times$  environment interactions, PSWH-201913 achieved the most significant kernel weight (98.50 g), followed by PSWH-201901 (97.43 g), PSWH-201915 (96.53 g), PSWH-201903 (94.20 g), and PSWH-201905 (94.16 g). Conversely, the smallest 200-kernel weight was observed in PSWH-201911 at UAP (66.73 g), which was comparable to PSWH-201901 (67.13 g), PSWH-201902 (69.26 g), PSWH-201912 (69.43 g), and the check cultivar CS-240 (69.20 g). Overall, the results confirmed substantial genotypic differences in 200-kernel weight, with evident environmental influences. These findings emphasize the presence of significant genetic variability in maize, indicating opportunities for improvement in seed index and related yield traits through targeted selection.

### **Grain yield**

Grain yield among genotypes ranged from 3,937 to 7,100 kg ha<sup>-1</sup>, while genotype  $\times$  environment interactions varied between 2,382 and 9,268 kg ha<sup>-1</sup> (Table 12). Based on genotype means, the highest yield was recorded in the F1 hybrid PSWH-201911 (7,100 kg ha<sup>-1</sup>), followed closely by PSWH-201905 (6,597 kg ha<sup>-1</sup>), PSWH-201912 (6,543 kg ha<sup>-1</sup>), PSWH-201903 (6,519 kg ha<sup>-1</sup>), and PSWH-201909 (6,480 kg ha<sup>-1</sup>). The lowest yield was observed in the check cultivar CS-240 (3,937 kg ha<sup>-1</sup>),

which was statistically comparable to Jalal (4,083 kg ha<sup>-1</sup>), PSWH-201916 (4,489 kg ha<sup>-1</sup>), and PSWH-201901 (4,700 kg ha<sup>-1</sup>).

Environmental means showed that genotypes produced higher yields at CCRI (7,448 kg ha<sup>-1</sup>) compared to UAP (3,781 kg ha<sup>-1</sup>). Within genotype × environment interactions, PSWH-201911 achieved the maximum yield at CCRI (9,268 kg ha<sup>-1</sup>), performing at par with PSWH-201905, PSWH-201909, PSWH-201903, PSWH-201912, PSWH-201904, and PSWH-201917. On the other hand, the lowest yield was obtained from the check cultivar Jalal at UAP (2,382 kg ha<sup>-1</sup>), followed by PSWH-201902, PSWH-201916, PSWH-201915, PSWH-201914, and PSWH-201917, with yields ranging between 2,712 and 3,260 kg ha<sup>-1</sup>. The remaining genotype × environment combinations produced intermediate values. These findings are consistent with the results of Bocianowski, Nowosad, and Rejek (2024), who reported significant differences in grain yield among 15 maize inbred lines across multiple environments in adaptability and stability studies. Their research, like the present study, highlighted substantial variability in the mean performance of maize hybrids, with genotypes, environments, and their interactions all exerting significant effects on grain yield.

### **Harvest index**

Harvest index among genotypes ranged from 28.71% to 43.41%, while genotype × environment interactions varied between 25.40% and 47.10% (Table 13). The F1 hybrids PSWH-201904 and PSWH-201905 both recorded the highest mean value (43.34%), which was statistically comparable to PSWH-201911 (43.00%), PSWH-201912 (42.85%), PSWH-201903 (42.75%), PSWH-201908 (42.20%), and the check cultivar CS-240. In contrast, CS-240 showed the lowest value (28.71%), which is similar to that of the check cultivar Jalal (32.54%). Environmental means indicated that CCRI produced the highest average harvest index (41.57%), whereas UAP recorded the lowest (37.28%). Within genotype × environment interactions, PSWH-201911 achieved the maximum harvest index at CCRI (47.11%), which was statistically at par with PSWH-201913 (46.77%), PSWH-201909 (45.50%), PSWH-201917 (45.25%), PSWH-201904 (45.07%), PSWH-201905 (44.93%), PSWH-201912 (43.60%), and the check cultivar Babar. On the other hand, the lowest value was observed in CS-240 at CCRI (25.40%), followed by PSWH-201917 (29.90%), PSWH-201914 (29.33%), and Jalal (30.90%) when grown at UAP. Overall, PSWH-201905, PSWH-201911, and PSWH-201912 consistently demonstrated superior harvest index values. These results align with previous studies that have reported significant genotypic, environmental, and genotype × environment interaction effects on harvest index and related yield traits in maize across diverse conditions.

### **Genetic Parameters**

The genotypic and phenotypic variances were highest at UAP compared to CCRI in most of the traits. Nevertheless, genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV)

showed the highest values at equal frequencies at both sites. The parameters that showed improved values of GCV and PCV include grain yield (12.60, 23.21), ear height (10.54, 19.25), fresh ear weight (10.48, 21.94), and biological yield (9.58, 18.09), respectively, at UAP. The highest values of GCV and PCV were obtained for the parameters, 200 kernel weight (58.78% and 134.79%), grain yield (10.64% and 17.72%), and the number of rows of kernels on an ear (8.18% and 12.65%), at CCRI, respectively. At UAP and CCRI, the value of heritability and genetic gain was the highest of the seven traits. Values of heritability in the broad sense (bs) were 18.57, 50.00, 50.00, and 36.00 (harvest index, kernel rows per ear, and kernel rows per ear, respectively) at UAP. The traits had moderate to high heritability (b) values, including kernel rows per ear (50.00%), days to 50 per cent tasseling (49.80%), and days to 50 per cent silking (30.76%). Meanwhile, other variables showed low heritability values at UAP. In CCRI, various traits exhibited heritability ( $h^2$ ) ranging from 5.90% (biological yield) to 59.42% (primary leaf area). Parameters, including primary leaf area (59.42%), kernel rows per ear (41.74%), ear diameter (36.36%), grain yield (36.03%), days to 50% silking (31.71%), and kernel rows per ear (30.36%), had medium to high beta ( $\beta$ ) values. Meanwhile, the other variables also showed a low heritability value at CCRI.

The findings of this study confirmed substantial variability in heritability and genetic gain, demonstrating that the available breeding material contains sufficient genetic diversity. High estimates of both genotypic and phenotypic coefficients of variation (GCV and PCV), coupled with moderate heritability and genetic gain, were recorded for traits such as ear height, days to maturity, kernels per row, plant aspect, kernel rows per ear, and grain yield. These results suggest that these traits are likely to respond favorably to phenotypic selection in maize improvement programs.

### **Conclusion**

The current research has demonstrated significant differences among maize hybrids, with high genotype  $\times$  environment interactions observed in most traits and yield. Three-way crosses, such as PSWH-201905, PSWH-201911, PSWH-201912, and PSWH-201913, consistently outperformed in terms of grain yield, fresh ear weight, and harvest index, indicating that they can combine high productivity with expanded stability. Conversely, properties of earliness were found to have a negative correlation with yield, suggesting that selection has to be very careful in balancing maturity and productivity. The fact that heritability and genetic gain estimates were high in several traits indicated that sufficient genetic variability was available, providing a range of possibilities for successful selection in future breeding programs. The results address a significant gap in local studies, as they define the comparative advantages of three-way crosses in contrasting Pakistani settings. Three-way crosses are thus encouraged to be given priority in breeding programs to provide a combination of yield stability and flexibility in various agro-climatic regions. In this study, promising genotypes have

been generated, which will be developed through multi-location, multi-year trials before commercial release to confirm their stability. Additionally, breeding programs would need to combine early maturity and yield potential to enhance resilience to terminal drought stress and resource constraints. Such improved hybrids could play a crucial role in achieving sustainable maize production, increasing farmers' income and food security at the national level.

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### **Conflict of Interest**

The authors declare that no conflict of interest exists regarding the publication of this paper.

### **Ethical Statement**

The study was conducted in accordance with institutional and national guidelines. There was neither the use of an endangered species nor transgenic material in this study.

### **Author Contributions**

Data collection, manuscript preparation, and analysis were all conducted by all authors.

### **Data Availability**

Within the article, the data that justified the findings of this study are found. The corresponding author can supply additional information on reasonable request.

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**Table 3. Mean squares for pooled analysis of variance for various parameters in maize experimental hybrids in comparison to check cultivars at UAP and CCRI.**

Source of variation	Environments	Reps. within			Pooled Error	CV
		Environment	Genotypes	G × E		
Degree of freedom (d.f.)	1	4	19	19	76	%
Biological yield	1803243271.00*	19252741.00	6876499.87*	3674821.50N S	3368610.4 7	13.0 6

Fresh ear weight	496.95**	3.40	2.34**	1.91*	1.04	15.27
Ear length	84.67**	3.20	1.83NS	2.87**	1.17	6.29
Ear diameter	1.22**	0.07	0.11**	0.09*	0.05	4.74
Kernel rows per ear	0.30NS	12.27	4.48**	4.26**	1.37	8.44
Kernels per row	500.21**	44.17	44.64**	47.91**	19.89	11.87
200-seed weight	2448.94**	11.79	165.59*	163.39*	88.70	11.77
Grain yield	403465861.90**	9387558.00	4412975.20*	1579622.80**	829200.50	16.21
Harvest index	550.83NS	176.12	98.42**	56.47*	27.99	19.78

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\*\* , \* = Significant at  $P \leq 0.01$  and  $P \leq 0.05$ , respectively

**Table 4. Mean performance of maize experimental hybrids in comparison to check cultivars for ear height at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (cm)</b>
PSWH-201901	49.50	70.67	60.08
PSWH-201902	57.00	74.33	65.67
PSWH-201903	70.07	76.67	73.37
PSWH-201904	66.10	74.00	70.05
PSWH-201905	50.50	75.33	62.92
PSWH-201906	51.07	83.67	67.37
PSWH-201907	55.00	76.67	65.83
PSWH-201908	63.00	77.33	70.17
PSWH-201909	58.03	82.00	70.02
PSWH-201910	66.33	79.67	73.00
PSWH-201911	68.00	70.33	69.17
PSWH-201912	69.00	78.67	73.83
PSWH-201913	81.73	79.67	80.70
PSWH-201914	55.67	77.67	66.67
PSWH-201915	66.67	82.00	74.33
PSWH-201916	65.77	72.67	69.22
PSWH-201917	56.67	65.33	61.00
Hybrid means (cm)	61.77	76.28	-
<b>Check cultivars</b>			
Babar	57.33	72.00	64.67
Jalal	60.33	84.33	72.33
CS-240	52.00	82.67	67.33
Check means (cm)	56.55	79.67	-
LSD <sub>0.05</sub> Genotypes		8.76	
LSD <sub>0.05</sub> Environments		9.49	
LSD <sub>0.05</sub> G × E		13.43	

**Table 5. Mean performance of maize experimental hybrids in comparison to check cultivars for biological yield at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (kg ha<sup>-1</sup>)</b>
PSWH-201901	9115	18401	13758
PSWH-201902	7157	18956	13057
PSWH-201903	10952	19357	15155
PSWH-201904	10411	18463	14437
PSWH-201905	10633	19488	15060
PSWH-201906	9443	15235	12339
PSWH-201907	9289	17815	13552
PSWH-201908	10467	18316	14391
PSWH-201909	11537	19163	15350
PSWH-201910	10285	16912	13599
PSWH-201911	12932	19651	16292
PSWH-201912	11103	19226	15165
PSWH-201913	11059	16002	13530
PSWH-201914	11138	18166	14652
PSWH-201915	8833	18482	13658
PSWH-201916	9318	16182	12750
PSWH-201917	11354	18159	14757
Hybrid means (kg ha <sup>-1</sup> )	10296	18116	-
<b>Check cultivars</b>			
Babar	9780	16087	12934
Jalal	7831	17022	12426
CS-240	10806	17421	14113
Check means (kg ha <sup>-1</sup> )	9473	16843	-
LSD <sub>0.05</sub> Genotypes		2224	
LSD <sub>0.05</sub> Environments		2110	
LSD <sub>0.05</sub> G × E		2985	

**Table 6. Mean performance of maize experimental hybrids in comparison to check cultivars for fresh ear weight at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (kg)</b>
PSWH-201901	4.40	8.67	6.53
PSWH-201902	2.70	8.33	5.51

PSWH-201903	4.83	8.83	6.83
PSWH-201904	4.70	9.17	6.93
PSWH-201905	4.83	10.33	7.58
PSWH-201906	4.93	7.00	5.96
PSWH-201907	4.43	9.00	6.71
PSWH-201908	4.50	8.50	6.50
PSWH-201909	5.20	9.40	7.30
PSWH-201910	5.43	8.17	6.80
PSWH-201911	5.93	9.33	7.63
PSWH-201912	4.83	9.70	7.26
PSWH-201913	4.47	8.17	6.31
PSWH-201914	4.80	8.67	6.73
PSWH-201915	3.63	9.17	6.40
PSWH-201916	4.27	8.33	6.30
PSWH-201917	4.20	10.17	7.18
Hybrid means (kg)	4.59	8.88	-
<b>Check cultivars</b>			
Babar	4.17	7.00	5.58
Jalal	3.97	7.83	5.90
CS-240	6.47	8.33	7.40
Check means (kg)	4.87	7.72	-
LSD <sub>0.05</sub> Genotypes		0.93	
LSD <sub>0.05</sub> Environments		1.17	
LSD <sub>0.05</sub> G × E		1.65	

**Table 7. Mean performance of maize experimental hybrids in comparison to check cultivars for ear length at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (cm)</b>
PSWH-201901	15.93	21.33	18.63
PSWH-201902	16.13	18.37	17.25
PSWH-201903	16.67	17.57	17.12
PSWH-201904	15.87	18.47	17.17
PSWH-201905	15.83	17.67	16.75
PSWH-201906	16.43	16.50	16.47

PSWH-201907	15.17	18.43	16.80
PSWH-201908	16.17	17.47	16.82
PSWH-201909	16.30	16.13	16.22
PSWH-201910	16.10	17.80	16.95
PSWH-201911	17.47	17.13	17.30
PSWH-201912	17.77	18.33	18.05
PSWH-201913	16.33	17.87	17.10
PSWH-201914	15.53	18.20	16.87
PSWH-201915	16.63	18.57	17.60
PSWH-201916	16.87	17.40	17.13
PSWH-201917	16.93	18.57	17.75
Hybrid means (cm)	16.36	17.87	-
<b>Check cultivars</b>			
Babar	15.93	19.23	17.58
Jalal	16.53	17.00	16.77
CS-240	16.07	18.23	17.15
Check means (cm)	16.18	18.85	-
LSD <sub>0.05</sub> Genotypes		0.90	
LSD <sub>0.05</sub> Environments		1.24	
LSD <sub>0.05</sub> G × E		1.75	

**Table 8. Mean performance of maize experimental hybrids in comparison to check cultivars for ear diameter at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (cm)</b>
PSWH-201901	4.60	4.37	4.48
PSWH-201902	4.53	5.00	4.77
PSWH-201903	4.50	4.27	4.38
PSWH-201904	4.43	4.93	4.68
PSWH-201905	4.33	4.60	4.47
PSWH-201906	4.40	4.40	4.40
PSWH-201907	4.40	4.77	4.58
PSWH-201908	4.47	4.40	4.43
PSWH-201909	4.63	4.73	4.68

PSWH-201910	4.37	4.50	4.43
PSWH-201911	4.50	4.97	4.73
PSWH-201912	4.43	4.67	4.55
PSWH-201913	4.33	4.53	4.43
PSWH-201914	4.53	4.93	4.73
PSWH-201915	4.47	5.13	4.80
PSWH-201916	4.37	4.50	4.43
PSWH-201917	4.53	4.57	4.55
Hybrid means (cm)	4.46	4.66	-
<b>Check cultivars</b>			
Babar	4.43	4.70	4.57
Jalal	4.43	4.40	4.42
CS-240	4.37	4.73	4.55
Check means (cm)	4.41	4.61	-
LSD <sub>0.05</sub> Genotypes		0.13	
LSD <sub>0.05</sub> Environments		0.24	
LSD <sub>0.05</sub> G × E		0.35	

**Table 9. Mean performance of maize experimental hybrids in comparison to check cultivars for kernel rows per ear at UAP and CCRI.**

<b>F1 Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (#)</b>
PSWH-201901	15.33	12.00	13.67
PSWH-201902	15.00	12.33	13.67
PSWH-201903	14.67	13.67	14.17
PSWH-201904	12.00	13.67	12.83
PSWH-201905	12.67	12.33	12.50
PSWH-201906	14.33	13.00	13.67
PSWH-201907	15.33	15.33	15.33
PSWH-201908	12.67	13.33	13.00
PSWH-201909	13.00	14.33	13.67
PSWH-201910	14.33	12.33	13.33
PSWH-201911	12.67	14.67	13.67
PSWH-201912	14.00	15.33	14.67

PSWH-201913	14.33	16.67	15.50
PSWH-201914	12.67	14.00	13.33
PSWH-201915	12.00	13.67	12.83
PSWH-201916	14.00	16.00	15.00
PSWH-201917	14.00	15.00	14.50
Hybrid means (#)	13.71	13.98	-
<b>Check cultivars</b>			
Babar	14.00	12.33	13.17
Jalal	15.00	14.67	14.83
CS-240	14.33	13.67	14.00
Check means (#)	14.44	13.56	-
LSD <sub>0.05</sub> Genotypes		1.77	
LSD <sub>0.05</sub> Environments		1.34	
LSD <sub>0.05</sub> G × E		1.90	

**Table 10. Mean performance of maize experimental hybrids in comparison to check cultivars for kernels per row at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (#)</b>
PSWH-201901	40.00	34.00	37.00
PSWH-201902	34.67	31.67	33.17
PSWH-201903	42.33	29.00	35.67
PSWH-201904	41.67	36.33	39.00
PSWH-201905	39.00	41.00	40.00
PSWH-201906	39.33	33.00	36.17
PSWH-201907	33.67	36.33	35.00
PSWH-201908	44.67	39.00	41.83
PSWH-201909	41.33	39.33	40.33
PSWH-201910	38.33	35.00	36.67
PSWH-201911	39.67	36.00	37.83
PSWH-201912	47.33	32.33	39.83
PSWH-201913	33.67	32.67	33.17
PSWH-201914	44.00	35.67	39.83
PSWH-201915	40.33	35.00	37.67

PSWH-201916	37.33	29.33	33.33
PSWH-201917	40.00	39.33	39.67
Hybrid means (#)	39.41	35.37	-
<b>Check cultivars</b>			
Babar	40.33	29.67	35.00
Jalal	37.33	40.67	39.00
CS-240	37.33	42.33	39.83
Check means (#)	40.78	35.38	-
LSD <sub>0.05</sub> Genotypes		3.36	
LSD <sub>0.05</sub> Environments		5.12	
LSD <sub>0.05</sub> G × E		7.25	

**Table 11. Mean performance of maize experimental hybrids in comparison to check cultivars for 200-grain weight at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (g)</b>
PSWH-201901	67.13	97.43	82.28
PSWH-201902	69.27	74.00	71.63
PSWH-201903	74.63	94.20	84.42
PSWH-201904	72.03	83.60	77.82
PSWH-201905	78.67	94.17	86.42
PSWH-201906	83.87	80.27	82.07
PSWH-201907	72.30	88.47	80.38
PSWH-201908	89.70	83.10	86.40
PSWH-201909	75.40	79.87	77.63
PSWH-201910	73.07	79.90	76.48
PSWH-201911	66.73	79.60	73.17
PSWH-201912	69.43	77.67	73.55
PSWH-201913	73.40	98.50	85.95
PSWH-201914	77.23	87.10	82.17
PSWH-201915	78.27	96.53	87.40
PSWH-201916	87.50	79.13	83.32
PSWH-201917	83.50	86.03	84.77
Hybrid means (g)	76.01	85.86	-
<b>Check cultivars</b>			

Babar	73.33	71.37	72.35
Jalal	74.20	73.77	73.98
CS-240	69.20	84.87	77.03
Check means (g)	72.24	76.67	-
LSD <sub>0.05</sub> Genotypes		1.74	
LSD <sub>0.05</sub> Environments		10.82	
LSD <sub>0.05</sub> G × E		15.31	

**Table 12. Mean performance of maize experimental hybrids in comparison to check cultivars for grain yield at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (kg ha<sup>-1</sup>)</b>
PSWH-201901	3691	5709	4700
PSWH-201902	2712	8259	5486
PSWH-201903	4609	8428	6519
PSWH-201904	4339	8300	6320
PSWH-201905	4450	8744	6597
PSWH-201906	3855	6583	5219
PSWH-201907	3778	7115	5446
PSWH-201908	4367	7813	6090
PSWH-201909	4235	8740	6487
PSWH-201910	3609	7140	5375
PSWH-201911	4933	9268	7100
PSWH-201912	4685	8400	6543
PSWH-201913	3696	7497	5596
PSWH-201914	3219	7707	5463
PSWH-201915	3217	7521	5369
PSWH-201916	3126	5853	4489
PSWH-201917	3260	8268	5764
Hybrid means (kg ha <sup>-1</sup> )	3869	7726	-
<b>Check cultivars</b>			
Babar	4024	7401	5712
Jalal	2382	5784	4083
CS-240	3436	4437	3937
Check means (kg ha <sup>-1</sup> )	3281	5874	-

LSD <sub>0.05</sub> Genotypes	1553
LSD <sub>0.05</sub> Environments	1047
LSD <sub>0.05</sub> G×E	1481

**Table 13. Mean performance of maize experimental hybrids in comparison to check cultivars for harvest index at UAP and CCRI.**

<b>F<sub>1</sub> Populations</b>	<b>UAP</b>	<b>CCRI</b>	<b>Means (%)</b>
PSWH-201901	40.34	31.10	35.72
PSWH-201902	37.43	43.46	40.45
PSWH-201903	42.08	43.42	42.75
PSWH-201904	41.60	45.07	43.34
PSWH-201905	41.74	44.94	43.34
PSWH-201906	40.33	43.33	41.83
PSWH-201907	40.49	40.35	40.42
PSWH-201908	41.71	42.69	42.20
PSWH-201909	37.61	45.49	41.55
PSWH-201910	35.63	43.00	39.31
PSWH-201911	38.88	47.11	43.00
PSWH-201912	42.10	43.60	42.85
PSWH-201913	32.51	46.77	39.64
PSWH-201914	29.36	42.53	35.94
PSWH-201915	36.88	40.92	38.90
PSWH-201916	33.98	36.83	35.40
PSWH-201917	29.21	45.25	37.23
Hybrid means (%)	37.76	42.70	-
<b>Check cultivars</b>			
Babar	39.88	46.11	43.00
Jalal	30.92	34.17	32.54
CS-240	32.01	25.36	28.69
Check means (%)	34.27	35.21	-
LSD <sub>0.05</sub> Genotypes		6.08	
LSD <sub>0.05</sub> Environments		6.72	
LSD <sub>0.05</sub> G × E		8.60	