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EXPLOITATION OF HETEROTIC POTENTIAL AND COMBINING ABILITY FOR GENETIC ENHANCEMENT OF GRAIN YIELD IN MAIZE

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ABSTRACT
The present investigation was undertaken to evaluate the **performance, character association and stability of newly developed maize (*Zea mays* L.) genotypes** across diverse environments. The experimental material was evaluated at three environments, viz., **E_1 (Kolhapur), E_2 (Gurugram (Delhi NCR)) and E_3 (Jalna)**. Data were recorded for phenological, morphological and yield-contributing traits and subjected to analysis of variance, correlation analysis, path coefficient analysis, environmental index analysis and stability analysis following the Eberhart and Russell model. Considerable variability was observed among the genotypes for the characters studied. Pooled grain yield per plant ranged from **74.66 to 103.64 g**, indicating substantial scope for selection. Among the environments, Kolhapur was comparatively favourable for grain yield, with an environmental index of **0.99**, whereas Gurugram (Delhi NCR) was relatively unfavourable (**−1.03**) and Jalna was nearly average (**0.04**). Genotypic correlation analysis revealed that plant height had a consistent negative association with grain yield across Kolhapur, Gurugram (Delhi NCR) and Jalna, with correlation coefficients of **−0.353, −0.293 and −0.312**, respectively. Cob length and 100-seed weight also exhibited predominantly negative associations with grain yield. In contrast, number of kernels per row showed positive genotypic associations with grain yield at Kolhapur and Gurugram (Delhi NCR), although the relationship was negative at Jalna. Path coefficient analysis revealed considerable environmental variation in the contribution of yield components. Plant height showed a strong negative direct effect under Kolhapur and Jalna, whereas number of kernels per row exhibited a high positive direct effect (**0.573**) under Gurugram (Delhi NCR). Stability analysis demonstrated differential responses of genotypes to environmental changes. Genotypes possessing high mean performance, regression coefficient close to unity and low deviation from regression were considered broadly adapted, while genotypes with regression coefficients greater or less than unity were identified as relatively responsive to favourable or unfavourable environments, respectively. The study demonstrated that simultaneous consideration of mean performance, character association, direct effects and stability parameters is essential for identifying promising maize genotypes for wider and specific adaptation.

KEYWORDS: Maize, genotype × environment interaction, stability, environmental index, correlation, path coefficient, grain yield, Eberhart and Russell.

1. INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereal crops globally and possesses exceptional adaptability to diverse agro-ecological environments. It is cultivated across tropical, subtropical and temperate regions and is utilized extensively for food, feed, fodder and industrial applications. The crop is particularly important because of its high yield potential, broad genetic variability and diverse end uses. Maize originated through domestication from teosinte, and molecular and genetic evidence has established *Zea mays* ssp. *parviglumis* as the principal progenitor of cultivated maize (Doebley, 2004). The remarkable evolutionary diversification of maize has generated extensive genetic variation that continues to provide opportunities for crop improvement.

The increasing demand for maize grain for human consumption, livestock and poultry feed, starch, biofuel and other industrial products has created a continuing need for genetic improvement in productivity. In India, maize is cultivated in different seasons and production environments, including kharif, rabi and spring/summer production systems. The crop is consequently exposed to considerable environmental variation, making the development of high-yielding and broadly adapted hybrids an important objective of maize breeding. Genetic improvement of grain yield, however, is complex because yield is a quantitative trait controlled by several genes and strongly influenced by environmental conditions. Therefore, efficient identification of genetically superior parents and their appropriate cross combinations is essential for maximizing breeding progress.

Hybrid breeding has played a central role in increasing maize productivity because maize exhibits substantial heterosis. Heterosis refers to the superior performance of a hybrid relative to its parental genotypes and may be expressed through increased grain yield, biomass, growth rate, fertility, adaptation and other agronomically important attributes. The phenomenon of hybrid vigour has long been recognized as a fundamental principle of maize improvement. Bruce (1910) and Davenport (1908) provided early genetic interpretations of hybrid vigour, while Shull (1914) established the term “heterosis” and emphasized the enhanced performance associated with hybridization. The subsequent development of inbred-line and hybrid breeding systems transformed maize improvement and enabled systematic exploitation of heterosis.

The magnitude of heterosis depends on the genetic constitution of the parental lines and the nature of interactions between their alleles. Consequently, the selection of appropriate parental lines is one of the most critical steps in hybrid breeding. Superiority of an inbred line based solely on its per se performance does not necessarily guarantee superior hybrid performance. The combining ability of a parent provides a more meaningful assessment of its usefulness in hybrid combinations. Sprague and Tatum (1942) partitioned combining ability into general combining ability (GCA) and specific combining ability (SCA). GCA represents the average performance of a parent in hybrid combinations and is primarily associated with additive genetic effects, whereas SCA represents the performance of particular cross combinations beyond that predicted from the GCA of their parents and is associated largely with non-additive genetic effects, including dominance and epistatic interactions.

Combining ability analysis therefore provides an important biometrical approach for understanding the genetic control of quantitative traits and for identifying promising parents and cross combinations. The relative magnitude of GCA and SCA variances provides useful information regarding the importance of additive and non-additive gene action in the expression of economically important traits. In maize, several studies have demonstrated that the relative importance of these components varies among traits and genetic materials. Sprague and Tatum (1942) showed that SCA effects were particularly important in previously selected material, whereas GCA was relatively more important in previously untested material. Subsequent investigations have confirmed the importance of both additive and non-additive genetic effects for grain yield and its component traits (Petrovic, 1998; Kara, 2001; Reddy et al., 2011; Abuali et al., 2012).

The Line × Tester mating design developed from the biometrical framework of Kempthorne (1957) provides an efficient method for evaluating a relatively large number of inbred lines using a limited number of testers. The method permits estimation of GCA effects of lines and testers as well as SCA effects of their hybrids. Thus, it reduces the number of crosses that need to be evaluated while providing useful information on parental combining ability and cross-specific performance. The Line × Tester approach has been extensively used in maize to identify superior combiners, determine the relative importance of additive and non-additive gene action, and select promising hybrids for further evaluation (Joshi et al., 2002; Panwar et al., 2013; Ahmed et al., 2017; Assefa et al., 2017).

Previous research has demonstrated substantial variation in combining ability among maize inbred lines. Joshi et al. (2002) identified specific inbred lines with desirable GCA effects for grain yield and associated traits, demonstrating the usefulness of combining ability analysis in early-generation hybrid selection. Pavan et al. (2011) reported significant GCA and SCA effects for several yield-related traits and identified promising parental combinations for heterosis breeding. Reddy et al. (2011) observed significant GCA and SCA effects for grain yield and its component traits, with SCA variance exceeding GCA variance for several characters, indicating an important contribution of non-additive genetic effects. Similarly, Abuali et al. (2012) observed significant GCA and SCA effects for several yield-related traits and reported variation in the relative contribution of additive and non-additive gene action among traits.

The usefulness of Line × Tester analysis becomes even greater when elite germplasm is evaluated under contrasting environmental conditions. Genotype × environment interactions can alter the relative performance of parental lines and hybrids and may influence the expression of GCA and SCA. Nass et al. (2000) demonstrated significant environmental effects and GCA × environment interaction in maize combining-ability studies, emphasizing that parental performance should be assessed across environments. Assefa et al. (2017), while evaluating maize lines and testers across three locations, observed significant variation among genotypes and significant GCA × location and SCA × location interactions for several traits. Such findings emphasize the importance of evaluating elite germplasm across environments before identifying parents or hybrids for wider breeding utilization.

Heterosis analysis complements combining ability analysis by identifying cross combinations that express superior performance over their parental or standard reference genotypes. The simultaneous consideration of per se performance, GCA, SCA and heterosis provides a more comprehensive basis for selecting hybrids with breeding and commercial potential. Beck et al. (1990), in a multi-environment evaluation of CIMMYT maize germplasm, demonstrated significant heterosis and GCA effects for important agronomic traits and highlighted the value of combining ability information for identifying useful heterotic patterns. More recent Line × Tester investigations have similarly reported considerable heterotic expression and significant combining ability effects for grain yield and its component traits (Ahmed et al., 2017; Ambikabathy et al., 2019; Nandhitha et al., 2018; Abenezer et al., 2020).

Grain yield in maize is determined by several interrelated yield components, including ear length, number of kernel rows per ear, number of kernels per row, seed weight and shelling percentage. Selection exclusively for grain yield may therefore be less efficient than simultaneous evaluation of yield and its component traits. Identification of parents combining desirable GCA for several traits and crosses exhibiting high SCA and heterosis for grain yield and associated characters can facilitate the development of superior hybrids and broaden the genetic base available for future breeding. Studies by Kapoor et al. (2014), Kumar et al. (2019), Mohamed (2020) and Mousa et al. (2021) have demonstrated the effectiveness of combining ability and heterosis analyses for identifying promising parental lines and hybrid combinations in maize.

Despite extensive progress in maize hybrid breeding, continuous evaluation of new elite inbred lines remains necessary because the value of a parental line is dependent on its genetic background, tester, target environment and the traits under consideration. The identification of superior combiners and heterotic cross combinations from newly available elite germplasm can therefore contribute substantially to breeding programmes aimed at improving grain yield and yield stability. In particular, information on GCA and SCA can help breeders distinguish parents with broad combining ability from cross-specific combinations that possess superior hybrid performance.

In the present investigation, elite maize inbred lines were evaluated using a Line × Tester mating design to dissect their combining ability and heterotic potential for grain yield and associated agronomic traits. The study focused on days to 50% tasselling, days to 50% silking, days to 75% dry husk, plant height, ear length, number of kernel rows per cob, number of kernels per row, 100-seed weight, shelling percentage and grain yield. These traits correspond directly with the experimental observations defined in the research programme. The major objectives were to estimate heterosis in the resulting cross combinations, determine GCA and SCA effects across environments, and identify outstanding parental lines and hybrids for utilization in subsequent maize breeding programmes.

The integration of heterosis estimates with GCA and SCA effects is expected to provide a clearer understanding of the genetic potential of the elite germplasm and facilitate the identification of promising parental combinations. Such information can be utilized to strengthen heterotic breeding strategies, improve the efficiency of parental selection and support the development of high-yielding maize hybrids adapted to diverse production environments.

MATERIALS AND METHODS

3.1 Experimental Material

The present investigation entitled **“Stability Analysis Studies in Newly Developed Genotypes of Maize”** was undertaken to evaluate the performance, genotype × environment interaction and stability of maize genotypes across diverse environments. The experimental material consisted of newly developed maize genotypes along with parental lines, testers, their crosses and standard checks. The material was evaluated for phenological, morphological and yield-contributing characters under different environments.

The experimental material represented considerable genetic variability for traits such as days to 50 per cent tasseling, days to 50 per cent silking, days to 75 per cent dry husk, plant height, cob length, shelling percentage, grain yield per plant, number of kernel rows per cob, number of kernels per row and 100-seed weight. Such variation among the genotypes formed the basis for assessing their performance and stability across environments.

3.2 Experimental Locations

The genotypes were evaluated in three contrasting environments:

Environment	Location
E_1	Kolhapur
E_2	Gurugram (Delhi NCR)
E_3	Jalna

The three locations represented contrasting environmental conditions. The environmental index analysis subsequently confirmed that the environments differed in their relative favourability for individual traits. For grain yield per plant, Kolhapur showed a positive environmental index (0.99), Gurugram (Delhi NCR) showed a negative index (−1.03), while Jalna showed a nearly neutral index (0.04).

3.3 Experimental Design and Layout

The experimental material was evaluated under replicated field conditions at each of the three environments. The genotypes were grown under appropriate agronomic and crop management practices recommended for maize at the respective experimental locations.

The experimental entries included the newly developed genotypes along with parental material, crosses and standard checks. The performance of individual genotypes was recorded separately in each environment, and the environment-wise data were subsequently used for statistical and stability analyses.

Important: Your Results file does not explicitly state the number of replications, plot dimensions, spacing or fertilizer dose. Therefore, these details should be inserted exactly according to your field experiment rather than assumed.

3.4 Observations Recorded

Observations were recorded on quantitative, phenological, morphological and yield-contributing characters. The characters considered in the analysis were:

1. Days to 50 per cent tasseling
2. Days to 50 per cent silking
3. Days to 75 per cent dry husk
4. Plant height (cm)
5. Cob length (cm)
6. Shelling percentage (%)
7. Grain yield per plant (g)
8. Number of kernel rows per cob
9. Number of kernels per row
10. 100-seed weight (g)
11. Days to maturity

The Results chapter specifically presents analyses for these phenological, morphological and yield-related characters.

3.4.1 Days to 50 per cent tasseling

Days to 50 per cent tasseling were recorded as the number of days from sowing until 50 per cent of the plants in a genotype exhibited pollen shedding.

3.4.2 Days to 50 per cent silking

Days to 50 per cent silking were recorded as the number of days from sowing until 50 per cent of the plants exhibited visible silks.

3.4.3 Days to 75 per cent dry husk

The number of days from sowing required for the genotype to attain approximately 75 per cent dry husk condition was recorded.

3.4.4 Plant height (cm)

Plant height was measured in centimetres from the ground level to the uppermost portion of the plant at maturity. The mean of the observations recorded from representative plants was used for statistical analysis.

3.4.5 Cob length (cm)

Cob length was measured in centimetres from the base to the tip of the cob after harvesting and dehusking. The mean value was calculated for each genotype.

3.4.6 Shelling percentage

Shelling percentage was determined from representative cobs by calculating the proportion of grain weight to ear weight.

Shelling percentage=Weight of grainWeight of ear×100\text{Shelling percentage} = \frac{\text{Weight of grain}}{\text{Weight of ear}}\times100

3.4.7 Grain yield per plant (g)

Grain yield obtained from individual representative plants was weighed after threshing and drying and expressed in grams per plant. Grain yield per plant was considered the **primary economic character** in the present investigation.

3.4.8 Number of kernel rows per cob

The number of kernel rows present on representative cobs was counted and expressed as number of rows per cob.

3.4.9 Number of kernels per row

The number of kernels present in representative kernel rows was counted and expressed as kernels per row.

3.4.10 100-seed weight (g)

A representative sample of 100 grains from each genotype was weighed and expressed in grams.

3.4.11 Days to maturity

Days to maturity were recorded as the number of days from sowing until the genotype attained physiological maturity. The variation in maturity duration was used to assess differences in phenological behaviour among the genotypes.

3.5 Statistical Analysis

The observations recorded in each environment were subjected to statistical analysis to determine the magnitude of variation among genotypes and environments and to assess the association of different characters with grain yield.

The following statistical analyses were performed:

1. Analysis of variance
2. Mean performance analysis
3. Genotypic and phenotypic correlation coefficient analysis
4. Path coefficient analysis
5. Environmental index analysis
6. Genotype × environment interaction analysis

7. Stability analysis using the Eberhart and Russell model

The Results chapter confirms that individual-environment and pooled data were analysed to assess genetic variability, character association, contribution of yield components and stability across environments.

3.5.1 Analysis of Variance

Analysis of variance was performed separately for each environment to determine the significance of differences among genotypes for the characters studied. Pooled analysis was subsequently used to assess the effects of genotype, environment and genotype × environment interaction.

The presence of significant variation among genotypes was considered evidence of genetic variability, while differences among environments indicated differential environmental effects on genotype expression. The Results chapter confirms considerable variation among genotypes and environments.

3.5.2 Mean Performance

The mean performance of each genotype was calculated separately for each environment. Pooled means were obtained across environments to compare the overall performance of the genotypes.

The pooled performance was used to identify superior genotypes for phenological, morphological and yield-related traits. However, because genotype performance varied among environments, pooled mean performance was interpreted together with environmental response and stability parameters.

3.6 Correlation Coefficient Analysis

Genotypic and phenotypic correlation coefficients were estimated among grain yield per plant and its component characters for each environment.

The purpose of correlation analysis was to determine the **degree and direction of association between grain yield and its component traits** and to identify characters that could be used as indirect selection criteria for improving grain yield. The Results chapter confirms that correlation analysis was conducted separately for E_1 (Kolhapur), E_2 (Gurugram (Delhi NCR)) and E_3 (Jalna).

Genotypic correlation coefficients were used to assess the association attributable primarily to genetic causes, whereas phenotypic correlations represented the combined influence of genetic and environmental factors.

The significance of the correlation coefficients was tested at the appropriate levels of significance.

3.7 Path Coefficient Analysis

Path coefficient analysis was performed to partition the correlation coefficients into **direct and indirect effects** of different quantitative characters on grain yield per plant.

The analysis was conducted separately for Kolhapur (E_1), Gurugram (Delhi NCR) (E_2) and Jalna (E_3).

Grain yield per plant was considered the dependent variable, while the remaining quantitative characters were considered causal variables.

The direct effect of each character on grain yield was estimated, and the indirect effects through other characters were subsequently determined.

The residual effect was calculated to account for the proportion of variation in grain yield not explained by the characters included in the path analysis.

The Results demonstrated that path coefficients differed substantially among environments. For example, plant height had a strong negative direct effect under Kolhapur and Jalna, whereas number of kernels per row showed a high positive direct effect under Gurugram (Delhi NCR).

3.8 Environmental Index

Environmental indices were calculated to determine the relative favourability of each environment for the expression of individual characters.

The environmental index for an environment was estimated as the deviation of the environmental mean from the overall mean of the character.

A **positive environmental index** indicated a relatively favourable environment, whereas a **negative environmental index** indicated a relatively unfavourable environment for the expression of the respective character.

For grain yield per plant, Kolhapur had an environmental index of **0.99**, Gurugram (Delhi NCR) **−1.03** and Jalna **0.04**, demonstrating substantial differences in environmental favourability.

3.9 Genotype × Environment Interaction

The performance of genotypes across environments was analysed to determine the magnitude of genotype × environment interaction (G × E).

The differences in genotype performance among Kolhapur, Gurugram (Delhi NCR) and Jalna were considered indicative of differential environmental responses. Partitioning of G × E interaction into linear and non-linear components was used to understand the responsiveness and predictability of genotype performance across environments.

3.10 Stability Analysis

Stability analysis was performed using the **Eberhart and Russell (1966) model** to identify genotypes possessing

wide or specific adaptation across the three environments.
The stability of each genotype was assessed using three parameters:

1. **Genotypic mean (μ\mu)**
2. **Regression coefficient (bib_i)**
3. **Deviation from regression (Sdi2S^2_{di})**

The model was based on the linear regression of genotype performance on the environmental index.
According to the Eberhart and Russell model, a genotype with **high mean performance, bib_i approximately equal to 1.0 and non-significant/low Sdi2S^2_{di}** is considered to have good stability and wider adaptation. Genotypes with **bi>1.0b_i>1.0** are considered more responsive to favourable environments, whereas genotypes with **bi<1.0b_i<1.0** are relatively better adapted to unfavourable environments.
The stability parameters were estimated for individual characters, including phenological traits, plant height, cob length, shelling percentage, grain yield per plant, number of kernel rows per cob, number of kernels per row and 100-seed weight.

3.11 Criteria for Identification of Stable Genotypes

Genotypes were classified according to their mean performance, regression coefficient and deviation from regression.

Stability category	Mean	Regression coefficient (bib_i)	Deviation (Sdi2S^2_{di})
Widely adapted/stable	High	≈ 1.0	Low/non-significant
Favourable environment adapted	High	> 1.0	Low/non-significant
Unfavourable environment adapted	High	< 1.0	Low/non-significant
Unpredictable	Variable	Any	Significant/high

This approach allowed identification of genotypes possessing **broad adaptation as well as specific adaptation to favourable or unfavourable environments**.

3. RESULTS AND DISCUSSION

The present investigation was conducted to assess the performance, character association and stability of maize genotypes across three contrasting environments, viz., **E_1 (Kolhapur), E_2 (Gurugram (Delhi NCR)) and E_3 (Jalna)**. The experimental material exhibited considerable variation for phenological, morphological and yield-related traits. The data were analysed for mean performance, genotypic and phenotypic correlations, path coefficients, environmental indices and stability parameters.

3.1 Analysis of Variance and Genetic Variability

The analysis of variance revealed considerable variation among the maize genotypes for the characters studied, indicating the presence of useful variability in the experimental material. The major differences were observed for days to 50 per cent tasseling, days to 50 per cent silking, days to 75 per cent dry husk, plant height, cob length, shelling percentage, grain yield per plant, number of kernel rows per cob, number of kernels per row and 100-seed weight.
The pooled range was particularly wide for **grain yield per plant (74.66–103.64 g), plant height (156.67–183.33 cm), cob length (63.33–84.17 cm) and 100-seed weight (20.33–25.00 g)**. Such variability is important from a breeding perspective because it provides scope for selection of superior genotypes and identification of desirable genetic combinations.
The environments also differed considerably in their effects on genotype performance. For grain yield per plant, Kolhapur recorded a positive environmental index of **0.99**, whereas Gurugram (Delhi NCR) recorded **−1.03** and Jalna recorded **0.04**. Thus, Kolhapur was relatively favourable for grain production, Gurugram (Delhi NCR) was comparatively unfavourable and Jalna represented an environment close to the overall environmental mean.
The differential environmental response provides evidence that genotype performance cannot be interpreted solely from a single location. Such environmental variation is particularly important in stability analysis because genotypes may differ in their response to changing environmental conditions. Similar importance of genotype, environment and genotype × environment interaction has been reported in maize stability studies cited in the source document.

3.2 Mean Performance of Genotypes

Considerable differences were observed among the genotypes for phenological, morphological and yield-contributing characters. The pooled values ranged from **50.50 to 58.17 days for days to 50 per cent tasseling**, **52.50 to 60.17 days for days to 50 per cent silking**, and **92.17 to 99.83 days for days to 75 per cent dry husk**. Plant height ranged from **156.67 to 183.33 cm**, while cob length ranged from **63.33 to 84.17 cm**. Shelling percentage varied from **80.95 to 86.02 per cent**, whereas grain yield per plant ranged from **74.66 to 103.64 g**. Number of kernel rows per cob, kernels per row and 100-seed weight ranged from **14.33–15.50, 30.83–37.83 and**

20.33–25.00 g, respectively.
The overall pooled means were **54.64 days for tasseling, 56.64 days for silking, 96.30 days for 75 per cent dry husk, 166.91 cm for plant height, 72.43 cm for cob length, 83.54 per cent for shelling, 87.96 g for grain yield per plant, 15.02 rows per cob, 34.45 kernels per row and 22.36 g for 100-seed weight**.

3.2.1 Days to 50 per cent tasseling

Days to 50 per cent tasseling ranged from **50.50 to 58.17 days**, with an overall mean of **54.64 days**. The earliest tasseling was recorded in **L2 × T3 (50.50 days)**, followed by L4, L2 × T2 and L1 × T2. The latest value was recorded by T5 (58.17 days). Several experimental genotypes were earlier than the checks, indicating useful variability for earliness.
The variation in tasseling duration provides an opportunity to select genotypes according to the desired crop duration. However, the results suggest that earliness should not be considered independently because reproductive duration showed only weak and inconsistent association with grain yield across environments.

3.2.2 Days to 50 per cent silking

Days to 50 per cent silking ranged from **52.50 to 60.17 days**, with a mean of **56.64 days**. L2 × T3 was the earliest genotype for silking (52.50 days), followed by L5 × T2, L2 × T2 and L3 × T4. In contrast, L3 × T3 showed comparatively late silking (59.83 days). Several experimental crosses were earlier than the standard checks.
The relatively early silking of L2 × T3 was consistent with its early tasseling behaviour. The association between tasseling and silking further indicated that reproductive development was closely interconnected. Nevertheless, silking duration had only a weak association with grain yield and therefore should be considered together with other yield attributes.

3.2.3 Days to 75 per cent dry husk

The pooled values for days to 75 per cent dry husk ranged from **92.17 to 99.83 days**, indicating useful variation in maturity behaviour. Jalna was relatively favourable for this character, as indicated by its positive environmental index of **0.50**, whereas Kolhapur and Gurugram (Delhi NCR) showed negative indices.
The observed variation provides scope for selection for appropriate maturity duration. Early maturity may be advantageous where short-duration maize is required, but maturity should be considered together with grain yield and stability.

3.2.4 Plant height

Plant height exhibited substantial variation among the genotypes. The pooled values ranged approximately from **156.67 to 183.33 cm**. The cross **L3 × T5** was particularly notable, recording a high plant height together with superior cob length and shelling percentage. However, the correlation analysis revealed that greater plant height was not necessarily favourable for grain yield. Plant height showed a significant negative genotypic correlation with grain yield at Kolhapur (**r = −0.353**), Gurugram (Delhi NCR) (**r = −0.293**) and Jalna (**r = −0.312**).
Thus, moderate plant stature combined with high grain yield and stability may be preferable rather than selecting solely for taller plants.

3.2.5 Cob length

Cob length varied from **63.33 to 84.17 cm**, with a pooled mean of **72.43 cm**. Among the crosses, L3 × T5 and L5 × T5 recorded particularly high values of **84.17 cm**, while L2 × T1 recorded the lowest value among the crosses. Despite the high cob length of some crosses, cob length showed a predominantly negative association with grain yield across the environments. The genotypic correlations with grain yield were **−0.261 at Kolhapur, −0.261 at Gurugram (Delhi NCR) and −0.162 at Jalna**.
Therefore, longer cobs alone may not guarantee higher productivity, and cob length should be evaluated along with kernel number and other yield components.

3.2.6 Shelling percentage

Shelling percentage ranged from approximately **80.62 to 85.68 per cent**, with an overall mean of **83.10 per cent** in the corresponding pooled analysis. L3 × T3 recorded the highest pooled shelling percentage (**85.68%**), followed by L4 × T4 and L5 × T4, whereas L5 × T2 recorded the lowest value among the crosses.
The genotypic association of shelling percentage with grain yield was negative in all three environments: **−0.103 at Kolhapur, −0.195 at Gurugram (Delhi NCR) and −0.149 at Jalna**.
This indicates that improvement in shelling percentage alone may not necessarily increase grain yield and should therefore be combined with other favourable yield attributes.

3.2.7 Grain yield per plant

Grain yield per plant was the most important economic trait. The pooled grain yield ranged from **74.66 to 103.64 g**, with an overall mean of **87.96 g**. Among the parental material, T3 recorded the highest value (**103.64 g**), followed by L5 (**102.69 g**). Among the crosses, L2 × T4 recorded **97.36 g**, L1 × T3 **98.47 g**, and L3 × T5 **94.61 g**. Check 1 and Check 2 recorded **89.05 and 96.41 g**, respectively. Thus, some experimental genotypes and crosses performed comparably with or better than the checks.
The substantial variation for grain yield indicates useful scope for selection. However, the environmental index demonstrated considerable environmental influence, emphasizing that superior mean yield should be accompanied by desirable stability.

3.2.8 Number of kernel rows per cob

The number of kernel rows per cob showed comparatively narrow variation, ranging from **14.33 to 15.50**, with a pooled mean of **15.02 rows per cob**. Its association with grain yield was weak and environment dependent. The

genotypic correlation was negative at Kolhapur (**−0.034**) but positive at Gurugram (Delhi NCR) (**0.069**) and Jalna (**0.063**).
Therefore, this character alone may not provide a consistent criterion for selection for higher grain yield.

3.2.9 Number of kernels per row

The pooled number of kernels per row ranged from **30.83 to 37.83**, with a mean of **34.45 kernels per row**. Considerable variation among genotypes provided scope for selection.
The genotypic correlation with grain yield was positive at Kolhapur (**0.042**) and Gurugram (Delhi NCR) (**0.065**) but negative at Jalna (**−0.066**). Interestingly, although the correlation under Gurugram (Delhi NCR) was small, path analysis showed a high positive direct effect of **0.573**, indicating that this character may contribute directly to grain yield under favourable conditions.

3.2.10 100-seed weight

The pooled 100-seed weight ranged from **20.33 to 25.00 g**, with an overall mean of **22.36 g**. The difference between extreme genotypes was approximately **4.67 g**, demonstrating useful variability for seed weight. L5 × T2, L5 × T4 and L5 × T5 recorded comparatively high values.
However, 100-seed weight exhibited a consistently negative genotypic association with grain yield: **−0.251 at Kolhapur, −0.229 at Gurugram (Delhi NCR) and −0.094 at Jalna**.
Thus, greater seed weight should not be used as an independent selection criterion for grain yield in the present material.

3.4 Path Coefficient Analysis

Path coefficient analysis was conducted to separate the correlations into direct and indirect effects of different characters on grain yield per plant. The analysis revealed substantial differences in the relative contribution of traits among the three environments.

3.4.1 Kolhapur

Under Kolhapur, **plant height recorded the highest negative direct effect (−0.321)**, followed by 100-seed weight (−0.276) and shelling percentage (−0.136). The negative direct effect of plant height corresponded with its significant negative genotypic correlation with grain yield, indicating that its unfavourable association was largely attributable to its direct effect.
Days to tasseling, days to silking and days to 75 per cent dry husk each recorded small positive direct effects of **0.039**, while kernels per row recorded a positive direct effect of **0.034**. The residual effect was **0.885**, indicating that a considerable proportion of variation in grain yield remained unexplained by the characters included in the analysis.

3.4.2 Gurugram (Delhi NCR)

Under Gurugram (Delhi NCR), the pattern was markedly different. **Number of kernels per row recorded the highest positive direct effect (0.573)** on grain yield. This was particularly important because its genotypic correlation with grain yield was only 0.065, demonstrating that a relatively weak correlation can nevertheless be associated with a strong direct contribution. Number of kernel rows per cob showed the highest negative direct effect (**−0.306**), followed by shelling percentage (**−0.282**). Plant height and cob length recorded negative direct effects of **−0.072 and −0.044**, respectively.
The residual effect was **0.761**, indicating that the traits included in the analysis explained more variation in grain yield than under Kolhapur, although a considerable proportion remained unexplained.

3.4.3 Jalna

Under Jalna, plant height again recorded the highest negative direct effect (**−0.3601**), followed by shelling percentage (**−0.1704**) and cob length (**−0.1104**). The negative direct effect of plant height agreed with its negative genotypic correlation with grain yield (**−0.312**).
The phenological traits each exhibited a positive direct effect of **0.0814**, while number of kernel rows per cob recorded a positive direct effect of **0.0662**. Number of kernels per row showed a negative direct effect (**−0.0614**) and 100-seed weight had a very small negative direct effect (**−0.0099**).
The residual effect was **0.8966**, indicating that a large proportion of grain-yield variation was attributable to factors not included in the present analysis.
The path analysis demonstrated clear **environment-specific contributions of yield components**. Plant height consistently exerted a strong negative direct influence under Kolhapur and Jalna, whereas kernels per row showed a pronounced positive direct effect under Gurugram (Delhi NCR).
These findings emphasize that selection for grain yield should not rely exclusively on simple correlations. Direct effects, indirect effects, mean performance and environmental stability should be considered simultaneously.

Table 4.8. Direct and Indirect Effects of Yield Components on Maize Grain Yield under E_1 (Kolhapur) Environment

Characters	Days to 50% Tasseling	Days to 50% Silking	Days to 75% Dry Husk	Plant Height	Cob Length	Shelling (%)	Kernel Rows/Cob	Kernels/Row	100-Seed Weight	Grain Yield/Plant
Days to 50% Tasseling	**0.039**	0.039	0.039	0.046	0.001	-0.029	-0.001	0.014	-0.007	0.140
Days to 50% Silking	0.039	**0.039**	0.039	0.046	0.001	-0.029	-0.001	0.014	-0.007	0.140
Days to 75% Dry Husk	0.039	0.039	**0.039**	0.046	0.001	-0.029	-0.001	0.014	-0.007	0.140
Plant Height (cm)	-0.006	-0.006	-0.006	**-0.321**	-0.007	-0.009	0.000	-0.002	0.004	-0.353*
Cob Length (cm)	-0.004	-0.004	-0.004	-0.157	**-0.014**	-0.020	0.000	-0.007	-0.053	-0.261
Shelling (%)	0.008	0.008	0.008	-0.022	-0.002	**-0.136**	-0.001	0.006	0.027	-0.103
Kernel Rows/Cob	-0.004	-0.004	-0.004	-0.004	0.000	0.017	**0.008**	0.003	-0.045	-0.034
Kernels/Row	0.016	0.016	0.016	0.021	0.003	-0.023	0.001	**0.034**	-0.043	0.042
100-Seed Weight (g)	0.001	0.001	0.001	0.004	-0.003	0.013	0.001	0.005	**-0.276**	-0.251

Residual effect = 0.885

Note: Bold diagonal values represent **direct effects**, while off-diagonal values represent **indirect effects** of the respective characters on grain yield per plant. The last column represents the correlation of each character with grain yield per plant. * indicates significance at the 5 per cent level.

Table 4.9. Direct and Indirect Effects of Yield Components on Maize Grain Yield under E_2 (Gurugram (Delhi NCR)) Environment

Characters	Days to 50% Tasseling	Days to 50% Silking	Days to 75% Dry Husk	Plant Height	Cob Length	Shelling (%)	Kernel Rows/Cob	Kernels/Row	100-Seed Weight	Grain Yield/Plant
Days to 50% Tasseling	**-0.028**	-0.028	-0.028	0.017	0.006	-0.064	-0.009	0.078	0.053	-0.003
Days to 50% Silking	-0.028	**-0.028**	-0.028	0.017	0.006	-0.064	-0.009	0.078	0.053	-0.003
Days to 75% Dry Husk	-0.028	-0.028	**-0.028**	0.017	0.006	-0.064	-0.009	0.078	0.053	-0.003
Plant Height (cm)	0.007	0.007	0.007	**-0.072**	-0.028	-0.050	0.089	0.234	-0.009	0.184
Cob Length (cm)	0.004	0.004	0.004	-0.045	**-0.044**	-0.029	0.080	0.168	-0.003	0.138
Shelling (%)	-0.006	-0.006	-0.006	-0.013	-0.005	**-0.282**	0.060	0.070	0.022	-0.167
Kernel Rows/Cob	-0.001	-0.001	-0.001	0.021	0.012	0.055	**-0.306**	-0.017	0.008	-0.229
Kernels/Row	-0.004	-0.004	-0.004	-0.029	-0.013	-0.034	0.009	**0.573**	0.031	0.525
100-Seed Weight (g)	-0.012	-0.012	-0.012	0.005	0.001	-0.048	-0.020	0.137	**0.130**	0.171

Residual effect = 0.761

Note: Bold diagonal values represent direct effects; the remaining values represent indirect effects through the corresponding characters. The last column represents the genotypic correlation of each character with grain yield per plant. E_2 = Gurugram (Delhi NCR).

Table 4.10. Direct and Indirect Effects of Yield Components on Maize Grain Yield under E_3 (Jalna) Environment

Characters	Days to 50% Tasseling	Days to 50% Silking	Days to 75% Dry Husk	Plant Height	Cob Length	Shelling (%)	Kernel Rows/Cob	Kernels/Row	100-Seed Weight	Grain Yield/Plant
Days to 50% Tasseling	**0.0814**	0.0814	0.0814	-0.0777	-0.0011	-0.0372	0.0031	-0.0045	0.0004	**0.1274**
Days to 50% Silking	0.0814	**0.0814**	0.0814	-0.0777	-0.0011	-0.0372	0.0031	-0.0045	0.0004	**0.1274**
Days to 75% Dry Husk	0.0814	0.0814	**0.0814**	-0.0777	-0.0011	-0.0372	0.0031	-0.0045	0.0004	**0.1274**
Plant Height (cm)	0.0176	0.0176	0.0176	**-0.3601**	-0.0075	-0.0073	0.0034	0.0074	-0.0009	**-0.3124**
Cob Length (cm)	0.0008	0.0008	0.0008	-0.0246	**-0.1104**	-0.0128	-0.0003	-0.0140	-0.0027	**-0.1625**
Shelling (%)	0.0178	0.0178	0.0178	-0.0155	-0.0083	**-0.1704**	0.0021	-0.0107	0.0006	**-0.1488**
Kernel Rows/Cob	0.0038	0.0038	0.0038	-0.0186	0.0006	-0.0054	**0.0662**	0.0080	0.0005	**0.0629**
Kernels/Row	0.0059	0.0059	0.0059	0.0435	-0.0252	-0.0297	-0.0086	**-0.0614**	-0.0025	**-0.0662**
100-Seed Weight (g)	-0.0037	-0.0037	-0.0037	-0.0338	-0.0306	0.0105	-0.0034	-0.0156	**-0.0099**	**-0.0939**

Residual effect = 0.8966

Note: Bold diagonal values indicate direct effects. The remaining values represent indirect effects through the corresponding characters. The last column represents the genotypic correlation with grain yield per plant. E_3 = Jalna.

3.5 Environmental Indices

Environmental indices demonstrated that the three environments differed substantially in their favourability for individual characters.

For grain yield per plant, **Kolhapur was the most favourable environment (0.99)**, **Gurugram (Delhi NCR) was unfavourable (−1.03)** and **Jalna was nearly average (0.04)**.

Gurugram (Delhi NCR) was particularly favourable for **plant height (1.00), cob length (1.02) and 100-seed weight (0.36)**, whereas Jalna was favourable for **days to 75 per cent dry husk (0.50) and kernels per row (0.75)**. Kolhapur was favourable for shelling percentage and grain yield.

These results clearly demonstrate that environmental favourability was **trait specific**. No single environment was uniformly favourable for all characters. This environmental contrast provided an appropriate basis for assessing genotype × environment interaction and stability.

3.6 Stability Analysis

Stability analysis was performed using the **Eberhart and Russell model**, considering genotype mean, regression coefficient (bib_i) and deviation from regression (Sdi2S^2_{di}). The analysis demonstrated considerable differences among genotypes in their response to environmental changes. A genotype with **high mean performance, bib_i close to unity and low/non-significant Sdi2S^2_{di}** was considered widely adapted and stable. Genotypes with **bi>1.0b_i>1.0** were regarded as more responsive to favourable environments, whereas those with **bi<1.0b_i<1.0** were considered relatively better suited to unfavourable environments.

3.6.1 Stability for phenological traits

The stability parameters for days to 50 per cent tasseling, days to 50 per cent silking and days to 75 per cent dry husk showed differential environmental responsiveness among genotypes. Genotypes with regression coefficients close to unity and low deviations from regression showed comparatively predictable performance.

The presence of genotypes with both higher and lower regression coefficients indicated differential sensitivity to environmental changes. This variability is useful for identifying genotypes adapted to either broad or specific environmental conditions.

3.6.2 Stability for plant height

Genotypes differed in their response for plant height across environments. Those having regression coefficients near unity and low Sdi2S^2_{di} exhibited relatively stable performance. The occurrence of both high and low regression coefficients indicated environmental sensitivity among the genotypes.

3.6.3 Stability for cob length

For cob length, genotypes differed in mean performance and regression coefficient. Genotypes possessing high cob length, bib_i close to unity and low deviation from regression were considered desirable for wider adaptation. Genotypes with bi>1b_i>1 were more responsive to favourable environments, whereas those with bi<1b_i<1 were relatively less responsive.

3.6.4 Stability for shelling percentage

The stability analysis indicated differential response of genotypes for shelling percentage. Genotypes with desirable shelling percentage, regression coefficient near unity and low deviation from regression were considered comparatively stable.

3.6.5 Stability for grain yield per plant

Grain yield per plant was the principal trait for stability assessment. Since Kolhapur was favourable, Gurugram (Delhi NCR) unfavourable and Jalna nearly average for grain yield, the environments provided a useful gradient for identifying differential adaptation.

Genotypes with high grain yield, bib_i close to unity and Sdi2S^2_{di} close to zero were considered broadly adapted. High-yielding genotypes with bi>1b_i>1 were considered particularly responsive to favourable environments such as Kolhapur, whereas genotypes with bi<1b_i<1, high mean yield and low deviation were considered comparatively suitable for unfavourable conditions such as Gurugram (Delhi NCR).

3.6.6 Stability for kernel rows per cob and kernels per row

For number of kernel rows per cob, genotypes with bib_i near unity and low deviation showed comparatively predictable performance. Since Gurugram (Delhi NCR) was favourable and Kolhapur unfavourable for this character, genotypes with bi>1b_i>1 were expected to respond more favourably under environments similar to Gurugram (Delhi NCR).

For kernels per row, Jalna showed the highest positive environmental index (**0.75**), indicating favourable conditions for expression of this character. Genotypes with bi>1b_i>1 and desirable means were therefore considered responsive to favourable environments, while those with bi<1b_i<1 and low deviation were relatively better suited to unfavourable environments.

3.6.7 Stability for 100-seed weight

Gurugram (Delhi NCR) was the most favourable environment for 100-seed weight, with an environmental index of **0.36**, followed by Jalna (**0.18**), while Kolhapur had a negative index (**−0.52**). Genotypes with high mean seed weight, bib_i near unity and low Sdi2S^2_{di} were considered stable.

3.7 Identification of Stable and Specifically Adapted Genotypes

The combined interpretation of genotype mean, regression coefficient and deviation from regression allowed classification of genotypes into three major adaptability groups:

1. **Wide adaptation:** high mean, bi≈1.0b_i\approx1.0 and low/non-significant Sdi2S^2_{di}.
2. **Adaptation to favourable environments:** high mean, bi>1.0b_i>1.0 and low/non-significant Sdi2S^2_{di}.
3. **Adaptation to unfavourable environments:** high mean, bi<1.0b_i<1.0 and low/non-significant Sdi2S^2_{di}.

Importantly, the genotype with the highest pooled mean was not necessarily the most stable genotype. Therefore, recommendation of superior maize genotypes should be based on the **combined consideration of productivity and stability**, rather than mean performance alone.

The analysis also demonstrated that stability should not be restricted to grain yield. Stability of cob length, shelling percentage, kernel rows per cob, kernels per row and 100-seed weight can provide additional information regarding the overall breeding value of a genotype.

The present investigation demonstrated substantial genetic and environmental variation among the maize genotypes. The wide variation observed for grain yield and associated traits provided adequate scope for identifying superior genotypes and useful breeding material.

The contrasting environmental indices confirmed that **Kolhapur, Gurugram (Delhi NCR) and Jalna differed in their relative favourability**, and their effects were character specific. In particular, the strong contrast in grain-yield environmental indices between Kolhapur (**0.99**) and Gurugram (Delhi NCR) (**−1.03**) provided an effective basis for evaluating environmental responsiveness and stability.

Correlation analysis showed that the association between yield and component traits was not consistent across environments. Plant height showed the most consistent negative relationship with grain yield, while kernels per row displayed a positive association under some environments. Path analysis further demonstrated that **plant height had a strong negative direct effect under Kolhapur and Jalna**, whereas **kernels per row had a strong positive direct effect under Gurugram (Delhi NCR)**.

The stability analysis reinforced the importance of multi-environment testing. Genotypes with high productivity, bib_i close to unity and low deviation from regression represent promising candidates for wider adaptation, while genotypes with bi>1b_i>1 or bi<1b_i<1 can be exploited for specific favourable or unfavourable environments, respectively.

Thus, the findings demonstrate that **high yield alone is not sufficient for identifying superior maize genotypes**. An effective selection strategy should integrate **mean performance, yield-component relationships, direct and indirect effects, environmental favourability and stability parameters**. Genotypes possessing desirable yield together with predictable performance across environments would have greater value for future multilocation testing and maize improvement programmes.

CONCLUSION

The present investigation demonstrated considerable genetic and environmental variation among the newly developed maize genotypes evaluated across **Kolhapur, Gurugram (Delhi NCR) and Jalna**. The wide variation observed for grain yield and associated characters indicated adequate scope for selection and utilization of promising genetic material in maize improvement programmes.

The three environments differed substantially in their favourability. **Kolhapur was the most favourable environment for grain yield**, as indicated by its positive environmental index (**0.99**), whereas Gurugram (Delhi NCR) was comparatively unfavourable (**−1.03**) and Jalna was close to the overall environmental mean (**0.04**). The environmental response was character specific, with Gurugram (Delhi NCR) being favourable for plant height, cob length and 100-seed weight, while Jalna was favourable for days to 75 per cent dry husk and number of kernels per row. Correlation analysis revealed that **plant height was consistently and negatively associated with grain yield** across all three environments. Cob length, shelling percentage and 100-seed weight also showed predominantly negative genotypic associations with grain yield. The relationship of kernels per row with grain yield was environment dependent.

Path analysis provided additional information beyond simple correlation. Plant height exerted a strong negative direct effect under Kolhapur and Jalna, whereas **number of kernels per row exhibited a strong positive direct effect of 0.573 under Gurugram (Delhi NCR)**. These findings demonstrate that indirect selection based solely on correlation coefficients may not always identify the most useful yield components. The stability analysis further demonstrated that genotype performance varied according to environmental conditions. Genotypes with **high mean performance, bib_i approximately equal to 1.0 and low/non-significant Sdi2S^2_{di}** were considered suitable for wider adaptation. Genotypes with bi>1.0b_i>1.0 were considered more responsive to favourable environments, whereas those with bi<1.0b_i<1.0 were relatively better suited to unfavourable environments.

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