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Trait Association and Path Coefficient Analysis Reveal Key Selection Traits for Grain Yield Improvement in Tropical Maize (*Zea mays* L.) Hybrids

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Grain yield in maize (*Zea mays L.*) is a complex quantitative trait governed by several interrelated morpho-physiological and yield-contributing characters. Understanding the relationships among these traits and their direct and indirect contributions to grain yield is essential for developing efficient selection strategies in hybrid breeding programmes. The present investigation was undertaken to estimate phenotypic and genotypic correlations and identify key yield-contributing traits influencing grain yield through correlation and path coefficient analyses in tropical maize hybrids. A total of 100 single-cross hybrids, developed from 20

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genetically diverse inbred lines and five elite testers, were evaluated along with their parents and four commercial checks across eleven environments representing major maize-growing regions of Telangana, Karnataka and Maharashtra during the kharif season of 2025. Combined analysis of variance revealed highly significant effects of environments, genotypes and genotype × environment interactions for all the traits studied, indicating substantial genetic variability and differential genotype responses across environments. Phenotypic and genotypic correlation analyses revealed that grain yield was significantly and positively associated with ear girth, number of kernels per row, ear length, plant height, ear height, hundred-kernel weight and number of kernel rows per ear, whereas flowering traits exhibited negative associations with grain yield. Genotypic correlations were generally stronger than the corresponding phenotypic correlations, suggesting that these relationships were predominantly governed by genetic factors. Path coefficient analysis identified ear girth as the trait exerting the highest positive direct effect on grain yield at the phenotypic level. At the genotypic level, days to 50% silking and the number of kernels per row exerted the largest positive direct effects, followed by hundred-kernel weight and the number of kernel rows per ear. The low residual effects indicated that the selected traits adequately explained the variation in grain yield. Overall, the findings indicate that simultaneous selection for number of kernels per row, hundred-kernel weight, ear girth and number of kernel rows per ear would be an effective breeding strategy for developing high-yielding and widely adapted tropical maize hybrids.

Keywords: Zea mays L.; tropical maize; grain yield; phenotypic correlation; genotypic correlation; path coefficient analysis; kernel number; ear girth; 100-kernel weight; hybrid breeding

1. Introduction

Maize (*Zea mays L.*) is one of the world's most important cereal crops because of its high yield potential, wide adaptability and versatile utilisation as food, feed and industrial raw material. As a C4 crop, maize exhibits superior photosynthetic efficiency, enabling it to produce higher biomass and grain yield under diverse agro-climatic conditions. Globally, it is cultivated on nearly 188 million hectares, with an annual production exceeding 1.4 billion tonnes. In India, maize ranks third after rice and wheat, occupying about 9.89 million hectares with a production of 31.65 million tonnes (Parihar et al., 2011). The increasing demand for maize from the feed, food processing and biofuel industries necessitates the continuous development of high-yielding and widely adapted hybrids capable of sustaining productivity under diverse tropical environments.

Grain yield is the primary objective of maize improvement programmes; however, it is a complex quantitative trait governed by numerous genes and strongly influenced by environmental conditions. The final grain yield is determined by the combined expression of several morpho-physiological and yield-related traits, each contributing directly or indirectly to productivity. Because of the complex inheritance of grain yield and its susceptibility to environmental variation, direct selection based solely on yield is often less efficient, particularly in the early stages of breeding. Therefore, identifying component traits that exhibit strong and consistent relationships with grain yield provides an effective approach for improving selection efficiency and accelerating genetic gain.

Recent evaluations of maize hybrids and inbred lines have likewise shown that the relationships between grain yield and its component traits can vary with the genetic material and testing environment, supporting population-specific assessment before indirect selection criteria are adopted (Shrestha et al., 2023; Korsa et al., 2024; Hasan et al., 2025).

Correlation analysis is an important biometrical tool for understanding the nature and magnitude of relationships among quantitative traits. Estimation of phenotypic and genotypic correlation coefficients helps breeders identify characters that are positively associated with grain yield and therefore can serve as indirect selection criteria. However, correlation analysis alone does not explain whether an association arises from the direct influence of a trait on grain yield or through indirect effects mediated by other correlated characters. Consequently, reliance solely on correlation coefficients may sometimes lead to misleading conclusions regarding the relative importance of different traits in determining grain yield.

To overcome this limitation, path coefficient analysis, originally proposed by Wright (1921) and adapted for plant breeding by Dewey and Lu (1959), partitions correlation coefficients into direct and indirect effects, thereby providing a better understanding of the causal relationships among yield and its component traits. Traits exhibiting high positive direct effects on grain yield are considered reliable selection criteria, whereas traits with substantial indirect effects indicate their influence through other associated characters. The combined use of correlation and path coefficient analyses therefore provides a more comprehensive understanding of the genetic relationships among agronomic traits and assists breeders in formulating efficient breeding strategies.

Recent maize studies have further demonstrated that the combined use of correlation and path coefficient analyses can distinguish traits showing strong associations with yield from those exerting substantial direct effects (Kumar et al., 2024; Pandey et al., 2026).

In tropical maize breeding programmes, the identification of key yield-contributing traits is particularly important because hybrids are expected to maintain superior performance under variable environmental conditions. Although several studies have reported associations among yield components in maize, the relative contribution of individual traits often differs depending on the genetic background and target production environments. Therefore, evaluating trait associations and their direct and indirect effects in newly developed tropical maize hybrids is essential for identifying reliable selection criteria for hybrid improvement.

However, information remains limited on whether the same morpho-physiological and yield-related traits consistently explain grain yield variation in newly developed tropical single-cross hybrids evaluated across multiple environments in southern India. This gap warrants a combined phenotypic and genotypic assessment of trait associations and their direct and indirect effects within the present hybrid set.

The present investigation was undertaken to estimate the associations among important morpho-physiological, yield and yield-related traits and to determine their direct and indirect contributions to grain yield through correlation and path coefficient analyses in tropical maize hybrids. The findings of this study are expected to provide useful information for identifying key selection traits and improving the efficiency of hybrid breeding programmes aimed at developing high-yielding maize hybrids adapted to tropical environments.

2. Materials and Methods

2.1 Plant Materials and Experimental Design

The experimental material comprised 100 single-cross maize hybrids developed by crossing twenty genetically diverse inbred lines with five elite testers (27AC, M6T, 1N06, DMK and 4DYW) following a Line × Tester mating design during the rabi season of 2024. The hybrids, along with their parental inbred lines and four commercial hybrid checks (P3524, DHM 117, DKC 9133 and DHM 119), were evaluated during the kharif season of 2025 across eleven environments representing major maize-growing regions of Telangana, Karnataka and Maharashtra, India. The test locations included Jagadevpur, Tunki Kalsa, Siddipet and Husnabad in Telangana; Shiggaon, Savadatti, Davanagere and Kamlapura in Karnataka; and Gadegoan, Phulambri and Vaijapur in Maharashtra. These environments represented diverse agro-climatic conditions, soil types and sowing windows, thereby providing a broad range of environmental conditions for evaluating the relationships among grain yield and its component traits in tropical maize hybrids.

The field experiment was conducted in a randomised complete block design (RCBD) with three replications in each environment. Each experimental plot consisted of a single row 4.0 m in length with a spacing of 60 cm between rows and 20 cm between plants. The crop was raised following the recommended agronomic package of practices for maize, including the application of 180 kg N, 75 kg P_2O_5 and 50 kg K_2O ha^{-1}, along with need-based plant protection measures.

2.2 Data Recording

Observations were recorded on fifteen morpho-physiological, yield and yield-related traits, namely days to 50% tasselling (DAYSHD), days to 50% silking (DAYSLK), anthesis-silking interval (ASI), days to maturity (brown husk) (DAYBHK), plant height (PLTHT), ear height (EARHT), ear length (EL), ear girth (EG), number of kernel rows per ear (NKRE), number of kernels per row (NKR), 100-kernel weight (HKW), grain moisture (MST), stay-green score at 85 days after sowing (SGNS85), stay-green score at 95 days after sowing (SGNS95) and grain yield per plant (GY).

Data on plant height, ear height, ear length, ear girth, number of kernel rows per ear, number of kernels per row and grain yield per plant were recorded from five randomly selected competitive plants in each plot. Observations on days to 50% tasselling, days to 50% silking, days to maturity, 100-kernel weight, grain moisture and stay-green scores were recorded on a plot basis following standard maize breeding procedures. Anthesis-silking interval was computed as the difference between days to 50% silking and days to 50% tasselling. Grain yield and 100-kernel weight were adjusted to 12% grain moisture prior to statistical analysis.

2.3 Statistical Analysis

Analysis of variance (ANOVA) was performed to assess the significance of variation among hybrids for all the traits studied. Mean values pooled over eleven environments were used to estimate phenotypic and genotypic correlation coefficients between grain yield and its component traits according to the method described by Al-Jibouri *et al.* (1958). The significance of correlation coefficients was tested at the 5% and 1% probability levels.

Path coefficient analysis was carried out using grain yield per plant as the dependent variable following the method proposed by Wright (1921) and subsequently adapted for plant breeding by Dewey and Lu (1959). The observed correlation coefficients were partitioned into direct and indirect effects to identify the traits exerting the greatest direct and indirect influence on grain yield, thereby facilitating the identification of reliable selection criteria for tropical maize hybrid improvement.

All statistical analyses were performed using WINDOSTAT version 9.3 (Indostat Services, Hyderabad, India).

3. Results and Discussion

3.1 Combined Analysis of Variance

The combined analysis of variance across eleven environments revealed highly significant ($P \leq 0.01$) effects of environments, genotypes and genotype × environment (G × E) interactions for all morpho-physiological, yield and yield-related traits (Table 1). The significant environmental effects indicated substantial variation among the test environments, reflecting differences in climatic and edaphic conditions across locations. Likewise, the highly significant genotypic effects demonstrated the presence of considerable genetic variability among the experimental hybrids, providing ample scope for effective selection and genetic improvement. The significant G × E interactions further indicated that genotype performance varied across environments, emphasising the importance of multi-environment testing for identifying stable and widely adapted maize hybrids. Similar observations have been reported by Kumar *et al.* (2014), who demonstrated significant genotype × environment interactions for grain yield and related traits in maize under multi-environment evaluation.

3.2 Phenotypic Correlation Analysis

Phenotypic correlation analysis revealed that grain yield was significantly and positively associated with ear girth (0.865), number of kernels per row (0.820), ear length (0.776), plant height (0.756), ear height (0.701), hundred-kernel weight (0.658), moisture content (0.568), number of kernel rows per ear (0.472), stay-green score at 85 DAS (0.291) and stay-green score at 95 DAS (0.239) (Table 2). These results indicate that improvements in ear architecture, kernel number and kernel weight contribute substantially to enhanced grain yield. In contrast, days to 50% tasselling (-0.426), days to 50% silking (-0.416) and anthesis–silking interval (-0.027) exhibited significant negative correlations with grain yield, suggesting that early-flowering genotypes with better flowering synchrony are advantageous in tropical environments. The strong positive associations among these traits indicate that improvement in one yield component is likely to result in simultaneous improvement of other yield-related characters, thereby facilitating indirect selection for higher grain yield.

Strong positive interrelationships were also observed among ear girth, ear length, number of kernels per row and hundred-kernel weight, indicating that simultaneous improvement of these component traits could effectively enhance grain productivity. These findings corroborate the observations of Kumar *et al.* (2014), Prakash *et al.* (2019), Singh *et al.* (2020), Khan and Mahmud (2021), Gogoi *et al.* (2025), and Beyene *et al.* (2026), who also identified ear-related traits, kernel number and other yield-contributing characters as major determinants of grain yield in maize through correlation and path coefficient analyses.

Table 1. Pooled analysis of variance for grain yield and its component traits in maize hybrids evaluated across eleven environments

Source of Variation	df	DAYSHD	DAYSLK	ASI	DAYSBHK	PLTHT	EARHT
Environments	10	3302.91 **	2837.12 **	113.78 **	9595.46 **	53972.49 **	44118.08 **
Genotypes	128	215.12 **	227.11 **	13.75 **	146.98 **	25860.77 **	13429.63 **
Env. * Genotypes	1280	6.3	8.67	2.88	12.08	123	81.4
Pooled Error	2816	3.2	3.8	1.5	5.65	76.08	44.31

Table 1. Pooled analysis of variance for grain yield and its component traits in maize hybrids evaluated across eleven environments (Contd..)

Source of Variation	df	EL	EG	NKRE	NKR	HKW	MST	SGNS85	SGNS95	GY
Environments	10	603.93 **	19.52 **	20.46 **	1652.66 **	4564.45 **	1969.63 **	124.37 **	114.97 **	169842.17 **
Genotypes	128	113.75 **	5.89 **	51.96 **	755.34 **	436.83 **	48.1 **	6.11 **	11.39 **	40218.01 **
Env. * Genotypes	1280	2.53	0.08	0.87	17.86	24.27	4.41	0.74	1.17	772.13
Pooled Error	2816	1.17	0.04	0.56	8.58	9.28	1.93	0.36	0.54	209.35

Days to 50 per cent tasseling (DAYSHD), days to 50 per cent silking (DAYSLK), anthesis–silking interval (ASI), days to maturity (brown husk) (DAYBHK), plant height (PLTHT), ear height (EARHT), ear length (EL), ear girth (EG), number of kernel rows per ear (NKRE), number of kernels per row (NKR), 100-kernel weight (HKW), moisture content (MST), stay-green score at 85 days after sowing (SGNS85), stay-green score at 95 days after sowing (SGNS95), and grain yield per plant (GY).

Table 2. Phenotypic correlation coefficients among morpho-physiological, yield and yield-related traits in tropical maize hybrids evaluated across eleven environments

	DAYSHD	DAYSLK	ASI	DAYBHK	PLTHT	EARHT	EL	EG	NKRE	NKR	HKW	MST	SGNS85	SGNS95	GY
DAYSHD	1.000	0.897 **	-0.095 **	0.352 **	-0.323 **	-0.296 **	-0.295 **	-0.388 **	-0.278 **	-0.336 **	-0.245 **	-0.211 **	0.021	0.071 **	-0.426 **
DAYSLK	0.897 **	**1.000**	0.348 **	0.332 **	-0.321 **	-0.287 **	-0.295 **	-0.373 **	-0.283 **	-0.325 **	-0.246 **	-0.196 **	-0.004	0.046 **	-0.416 **
ASI	-0.095 **	0.348 **	**1.000**	0.004	-0.028	-0.007	-0.033	-0.008	-0.043 **	-0.012	-0.032	0.003	-0.057 **	-0.052 **	-0.027 **
DAYBHK	0.352 **	0.332 **	0.004	**1.000**	0.015	0.013	0.055 **	0.007	-0.063 **	0.043 **	0.112 **	0.085 **	0.319 **	0.347 **	0.061 **
PLTHT	-0.323 **	-0.321 **	-0.028	0.015	**1.000**	0.904 **	0.645 **	0.689 **	0.361 **	0.685 **	0.483 **	0.502 **	0.183 **	0.154 **	0.756 **
EARHT	-0.296 **	-0.287 **	-0.007	0.013	0.904 **	**1.000**	0.553 **	0.664 **	0.299 **	0.654 **	0.450 **	0.468 **	0.130 **	0.106 **	0.701 **
EL	-0.295 **	-0.295 **	-0.033	0.055 **	0.645 **	0.553 **	**1.000**	0.583 **	0.271 **	0.774 **	0.517 **	0.445 **	0.221 **	0.178 **	0.776 **
EG	-0.388 **	-0.373 **	-0.008	0.007	0.689 **	0.664 **	0.583 **	**1.000**	0.605 **	0.689 **	0.580 **	0.557 **	0.233 **	0.180 **	0.865 **
NKRE	-0.278 **	-0.283 **	-0.043 **	-0.063 **	0.361 **	0.299 **	0.271 **	0.605 **	**1.000**	0.333 **	0.048 **	0.289 **	0.031 **	-0.024 **	0.472 **
NKR	-0.336 **	-0.325 **	-0.012	0.043 **	0.685 **	0.654 **	0.774 **	0.689 **	0.333 **	**1.000**	0.424 **	0.469 **	0.190 **	0.155 **	0.820 **
HKW	-0.245 **	-0.246 **	-0.032	0.112 **	0.483 **	0.450 **	0.517 **	0.580 **	0.048 **	0.424 **	**1.000**	0.370 **	0.355 **	0.320 **	0.658 **
MST	-0.211 **	-0.196 **	0.003	0.085 **	0.502 **	0.468 **	0.445 **	0.557 **	0.289 **	0.469 **	0.370 **	**1.000**	0.175 **	0.160 **	0.568 **
SGNS85	0.021	-0.004 **	-0.057 **	0.319 **	0.183 **	0.130 **	0.221 **	0.233 **	0.031 *	0.190 **	0.355 **	0.175 **	**1.000**	0.696 **	0.291 **
SGNS95	0.071 **	0.046	-0.052 **	0.347 **	0.154 **	0.106 **	0.178 **	0.180 **	-0.024	0.155 **	0.320 **	0.160 **	0.696 **	**1.000**	0.239 **
GY	-0.426 **	-0.416 **	-0.027 **	0.061 **	0.756 **	0.701 **	0.776 **	0.865 **	0.472 **	0.820 **	0.658 **	0.568 **	0.291 **	0.239 **	**1.000**

** Significant at 5% level; ** Significant at 1% level*

3.3 Genotypic Correlation Analysis

The magnitude of genotypic correlation coefficients was generally higher than the corresponding phenotypic correlation coefficients, indicating that the observed relationships among traits were predominantly governed by genetic factors and only partially influenced by environmental conditions (Table 3). Grain yield exhibited highly significant positive genotypic correlations with number of kernels per row (0.927), moisture content (0.922), ear girth (0.921), plant height (0.890), ear height (0.831), ear length (0.827), hundred-kernel weight (0.776), number of kernel rows per ear (0.590), stay-green score at 85 DAS (0.462) and stay-green score at 95 DAS (0.356). Conversely, days to 50% silking (-0.607), days to 50% tasselling (-0.588), anthesis–silking interval (-0.120) and days to maturity (brown husk) (-0.018) were negatively associated with grain yield.

The stronger genotypic associations compared with phenotypic correlations suggest that these relationships are largely heritable and can be effectively exploited through selection. Similar findings have been reported by Al-Jibouri *et al.* (1958), Kumar *et al.* (2014), Khan and Mahmud (2021), Mukhlisin *et al.* (2025), and Beyene *et al.* (2026), who demonstrated that grain yield is strongly associated with key agronomic and yield-related traits, thereby supporting indirect selection for yield improvement in maize.

3.4 Phenotypic Path Coefficient Analysis

Phenotypic path coefficient analysis partitioned the correlation coefficients into direct and indirect effects, thereby identifying the relative contribution of individual traits towards grain yield (Table 4). Ear girth (0.324) exerted the highest positive direct effect on grain yield, followed by number of kernels per row (0.246), ear length (0.184), hundred-kernel weight (0.178), number of kernel rows per ear (0.076) and plant height (0.070). Conversely, days to 50% tasselling (-0.061), days to 50% silking (-0.020) and anthesis–silking interval (-0.002) exhibited negative direct effects on grain yield.

The strong positive correlations of ear girth, ear length and number of kernels per row with grain yield were primarily attributable to their substantial positive direct effects, whereas plant height and ear height contributed indirectly through favourable associations with these yield components. These findings indicate that ear girth, number of kernels per row, ear length and hundred-kernel weight are the most reliable phenotypic selection criteria for improving grain yield. Similar conclusions have been drawn by Dewey and Lu (1959), Mohan *et al.* (2002), Brar *et al.* (2008), Jilo and Tulu (2019), Singh *et al.* (2020), and Beyene *et al.* (2026), who reported that path coefficient analysis effectively identifies traits with high direct effects on grain yield and provides reliable criteria for selection in maize breeding programmes.

3.5 Genotypic Path Coefficient Analysis

Genotypic path coefficient analysis revealed that days to 50% silking (0.543) and the number of kernels per row (0.487) exerted the largest positive direct effects on grain yield, followed by 100-kernel weight (0.363), the number of kernel rows per ear (0.184), moisture content (0.145), days to maturity (brown husk) (0.061), ear girth (0.050) and plant height (0.037) (Table 5). In contrast, days to 50% tasselling (-0.618), anthesis–silking interval (-0.144), ear height (-0.087), ear length (-0.009), stay-green score at 85 DAS (-0.016) and stay-green score at 95 DAS (-0.053) exerted negative direct effects on grain yield.

Although ear girth exhibited a strong positive genotypic correlation with grain yield, its direct effect was relatively small, indicating that its contribution to grain yield was largely mediated through favourable indirect effects, particularly via number of kernels per row, hundred-kernel weight and kernel rows per ear. In contrast, number of kernels per row and hundred-kernel weight exhibited both high positive correlations and substantial positive direct effects, confirming their pivotal role in determining grain yield. These results suggest that selection based on the number of kernels per row, hundred-kernel weight and kernel rows per ear would be highly effective for genetic improvement of grain yield in tropical maize hybrids. Similar findings have been reported by Dewey and Lu (1959), Mohan *et al.* (2002), Rafiq *et al.* (2010), Jilo and Tulu (2019), Singh *et al.* (2020), Khan and Mahmud (2021), and Beyene *et al.* (2026), who also identified key yield-contributing traits through path coefficient analysis and emphasised their importance in maize improvement programmes.

Table 3. Genotypic correlation coefficients among morpho-physiological, yield and yield-related traits in tropical maize hybrids evaluated across eleven environments

	DAYSHD	DAYSLK	ASI	DAYBHK	PLTHT	EARHT	EL	EG	NKRE	NKR	HKW	MST	SGNS85	SGNS95	GY
DAYSHD	**1.000**	0.973 **	-0.024 **	0.628 **	-0.445 **	-0.405 **	-0.425 **	-0.539 **	-0.407 **	-0.493 **	-0.405 **	-0.460 **	0.006 **	0.125 **	-0.588 **
DAYSLK	0.973 **	**1.000**	0.209 **	0.579 **	-0.450 **	-0.405 **	-0.440 **	-0.543 **	-0.421 **	-0.494 **	-0.451 **	-0.450 **	-0.047 **	0.078 **	-0.607 **
ASI	-0.024 **	0.209 **	**1.000**	-0.152 **	-0.042 **	-0.014 **	-0.086 **	-0.044 **	-0.085 **	-0.032 **	-0.218 **	0.020 **	-0.225 **	-0.188 **	-0.120 **
DAYBHK	0.628 **	0.579 **	-0.152 **	**1.000**	0.017 **	0.027 **	0.030 **	-0.097 **	-0.107 **	0.044 **	0.037 **	0.044 **	0.558 **	0.631 **	-0.018 **
PLTHT	-0.445 **	-0.450 **	-0.042 **	0.017 **	**1.000**	0.943 **	0.801 **	0.801 **	0.431 **	0.856 **	0.720 **	0.892 **	0.386 **	0.304 **	0.890 **
EARHT	-0.405 **	-0.405 **	-0.014 **	0.027 **	0.943 **	**1.000**	0.686 **	0.778 **	0.371 **	0.822 **	0.671 **	0.837 **	0.295 **	0.228 **	0.831 **
EL	-0.425 **	-0.440 **	-0.086 **	0.03 **	0.801 **	0.686 **	**1.000**	0.612 **	0.355 **	0.845 **	0.647 **	0.744 **	0.406 **	0.309 **	0.827 **
EG	-0.539 **	-0.543 **	-0.044 **	-0.097 **	0.801 **	0.778 **	0.612 **	**1.000**	0.716 **	0.800 **	0.681 **	0.871 **	0.351 **	0.249 **	0.921 **
NKRE	-0.407 **	-0.421 **	-0.085 **	-0.107 **	0.431 **	0.371 **	0.355 **	0.716 **	**1.000**	0.463 **	0.142 **	0.559 **	0.074 **	-0.070 **	0.590 **
NKR	-0.493 **	-0.494 **	-0.032 **	0.044 **	0.856 **	0.822 **	0.845 **	0.800 **	0.463 **	**1.000**	0.602 **	0.858 **	0.409 **	0.329 **	0.927 **
HKW	-0.405 **	-0.451 **	-0.218 **	0.037 **	0.720 **	0.671 **	0.647 **	0.681 **	0.142 **	0.602 **	**1.000**	0.669 **	0.598 **	0.547 **	0.776 **
MST	-0.460 **	-0.450 **	0.020 **	0.044 **	0.892 **	0.837 **	0.744 **	0.871 **	0.559 **	0.858 **	0.669 **	**1.000**	0.403 **	0.321 **	0.922 **
SGNS85	0.006 **	-0.047 **	-0.225 **	0.558 **	0.386 **	0.295 **	0.406 **	0.351 **	0.074 **	0.409 **	0.598 **	0.403 **	**1.000**	0.944 **	0.462 **
SGNS95	0.125 **	0.078 **	-0.188 **	0.631 **	0.304 **	0.228 **	0.309 **	0.249 **	-0.070 **	0.329 **	0.547 **	0.321 **	0.944 **	**1.000**	0.356 **
GY	-0.588 **	-0.607 **	-0.120 **	-0.018 **	0.890 **	0.831 **	0.827 **	0.921 **	0.590 **	0.927 **	0.776 **	0.922 **	0.462 **	0.356 **	**1.000**

** Significant at 5% level; ** Significant at 1% level*

Table 4. Direct (bold diagonal values) and indirect effects of morpho-physiological, yield and yield-related traits on grain yield at the phenotypic level in tropical maize hybrids

	DAYSHD	DAYSLK	ASI	DAYBHK	PLTHT	EARHT	EL	EG	NKRE	NKR	HKW	MST	SGNS85	SGN595
DAYSHD	**-0.061**	-0.055	0.006	-0.021	0.020	0.018	0.018	0.024	0.017	0.020	0.015	0.013	-0.001	-0.004
DAYSLK	-0.018	**-0.020**	-0.007	-0.007	0.006	0.006	0.006	0.007	0.006	0.006	0.005	0.004	0.000	-0.001
ASI	0.000	-0.001	**-0.002**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DAYBHK	0.012	0.011	0.000	**0.034**	0.001	0.000	0.002	0.000	-0.002	0.002	0.004	0.003	0.011	0.012
PLTHT	-0.023	-0.023	-0.002	0.001	**0.070**	0.063	0.045	0.048	0.025	0.048	0.034	0.035	0.013	0.011
EARHT	-0.004	-0.004	0.000	0.000	0.012	**0.013**	0.007	0.008	0.004	0.008	0.006	0.006	0.002	0.001
EL	-0.054	-0.054	-0.006	0.010	0.118	0.102	**0.184**	0.107	0.050	0.142	0.095	0.082	0.041	0.033
EG	-0.126	-0.121	-0.003	0.002	0.223	0.215	0.189	**0.324**	0.196	0.223	0.188	0.181	0.076	0.058
NKRE	-0.021	-0.022	-0.003	-0.005	0.027	0.023	0.021	0.046	**0.076**	0.025	0.004	0.022	0.002	-0.002
NKR	-0.083	-0.080	-0.003	0.011	0.168	0.161	0.190	0.169	0.082	**0.246**	0.104	0.115	0.047	0.038
HKW	-0.044	-0.044	-0.006	0.020	0.086	0.080	0.092	0.103	0.009	0.076	**0.178**	0.066	0.063	0.057
MST	-0.008	-0.007	0.000	0.003	0.018	0.017	0.016	0.020	0.010	0.017	0.013	**0.036**	0.006	0.006
SGNS85	0.001	0.000	-0.001	0.007	0.004	0.003	0.005	0.005	0.001	0.004	0.008	0.004	**0.022**	0.015
SGN595	0.001	0.001	-0.001	0.006	0.002	0.002	0.003	0.003	0.000	0.002	0.005	0.003	0.011	**0.016**
GY	-0.426	-0.416	-0.027	0.061	0.756	0.701	0.776	0.865	0.472	0.820	0.658	0.568	0.291	0.239
Partial R^2	0.026	0.008	0.000	0.002	0.053	0.009	0.143	0.281	0.036	0.201	0.117	0.020	0.006	0.004

R Square = 0.9059 Residual Effect = 0.3068

Table 5. Direct (bold diagonal values) and indirect effects of morpho-physiological, yield and yield-related traits on grain yield at the genotypic level in tropical maize hybrids

	DAYSHD	DAYSLK	ASI	DAYBHK	PLTHT	EARHT	EL	EG	NKRE	NKR	HKW	MST	SGNS85	SGN595
DAYSHD	**-0.618**	-0.601	0.015	-0.388	0.275	0.250	0.263	0.333	0.252	0.305	0.250	0.284	-0.004	-0.077
DAYSLK	0.528	**0.543**	0.114	0.315	-0.244	-0.220	-0.239	-0.295	-0.229	-0.268	-0.245	-0.245	-0.025	0.042
ASI	0.003	-0.030	**-0.144**	0.022	0.006	0.002	0.012	0.006	0.012	0.005	0.031	-0.003	0.032	0.027
DAYBHK	0.039	0.036	-0.009	**0.061**	0.001	0.002	0.002	-0.006	-0.007	0.003	0.002	0.003	0.034	0.039
PLTHT	-0.016	-0.017	-0.002	0.001	**0.037**	0.035	0.030	0.030	0.016	0.032	0.027	0.033	0.014	0.011
EARHT	0.035	0.035	0.001	-0.002	-0.082	**-0.087**	-0.060	-0.068	-0.032	-0.072	-0.058	-0.073	-0.026	-0.020
EL	0.004	0.004	0.001	0.000	-0.007	-0.006	**-0.009**	-0.006	-0.003	-0.008	-0.006	-0.007	-0.004	-0.003
EG	-0.027	-0.027	-0.002	-0.005	0.040	0.039	0.031	**0.050**	0.036	0.040	0.034	0.044	0.018	0.013
NKRE	-0.075	-0.078	-0.016	-0.020	0.080	0.068	0.066	0.132	**0.184**	0.085	0.026	0.103	0.014	-0.013
NKR	-0.240	-0.241	-0.015	0.022	0.417	0.400	0.412	0.389	0.225	**0.487**	0.293	0.418	0.199	0.160
HKW	-0.147	-0.164	-0.079	0.013	0.261	0.244	0.235	0.247	0.052	0.218	**0.363**	0.243	0.217	0.199
MST	-0.067	-0.065	0.003	0.006	0.130	0.122	0.108	0.127	0.081	0.125	0.097	**0.145**	0.059	0.047
SGNS85	0.000	0.001	0.004	-0.009	-0.006	-0.005	-0.007	-0.006	-0.001	-0.007	-0.010	-0.007	**-0.016**	-0.015
SGN595	-0.007	-0.004	0.010	-0.033	-0.016	-0.012	-0.016	-0.013	0.004	-0.017	-0.029	-0.017	-0.050	**-0.053**
GY	-0.588	-0.607	-0.120	-0.018	0.890	0.831	0.827	0.921	0.590	0.927	0.776	0.922	0.462	0.356
Partial R^2	0.363	-0.330	0.017	-0.001	0.033	-0.072	-0.007	0.046	0.109	0.451	0.282	0.134	-0.008	-0.019

R Square = 0.9981 Residual Effect = 0.0440

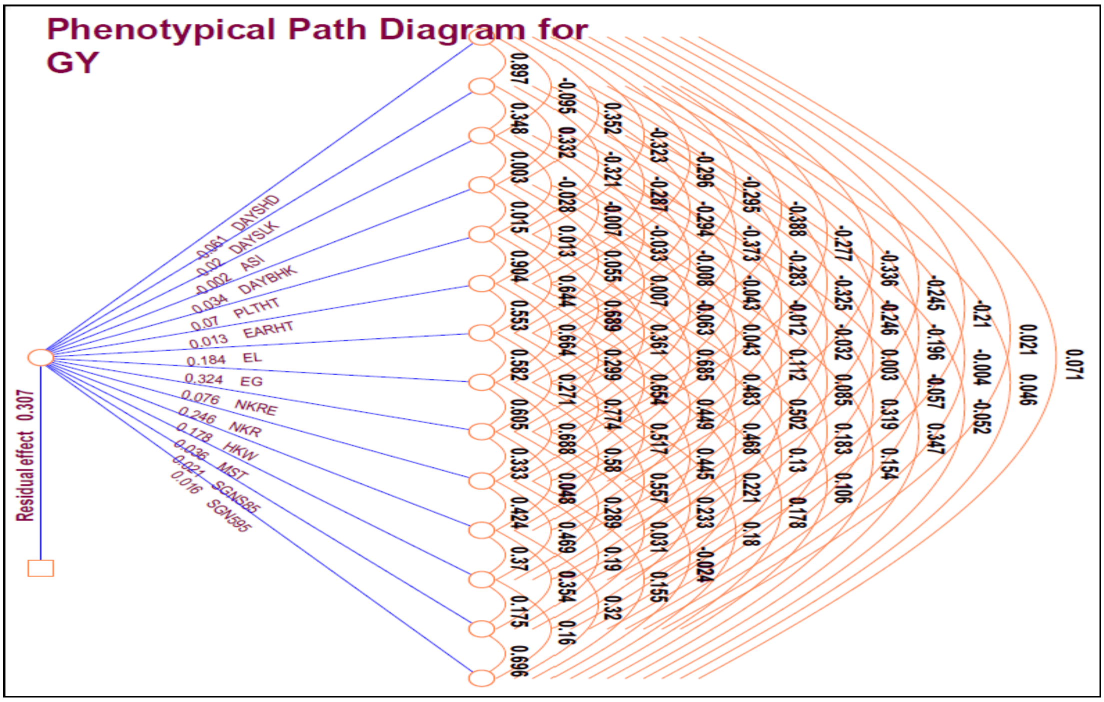

Fig. 1. Phenotypic path diagram for grain yield and its component traits in maize (pooled over 11 environments)

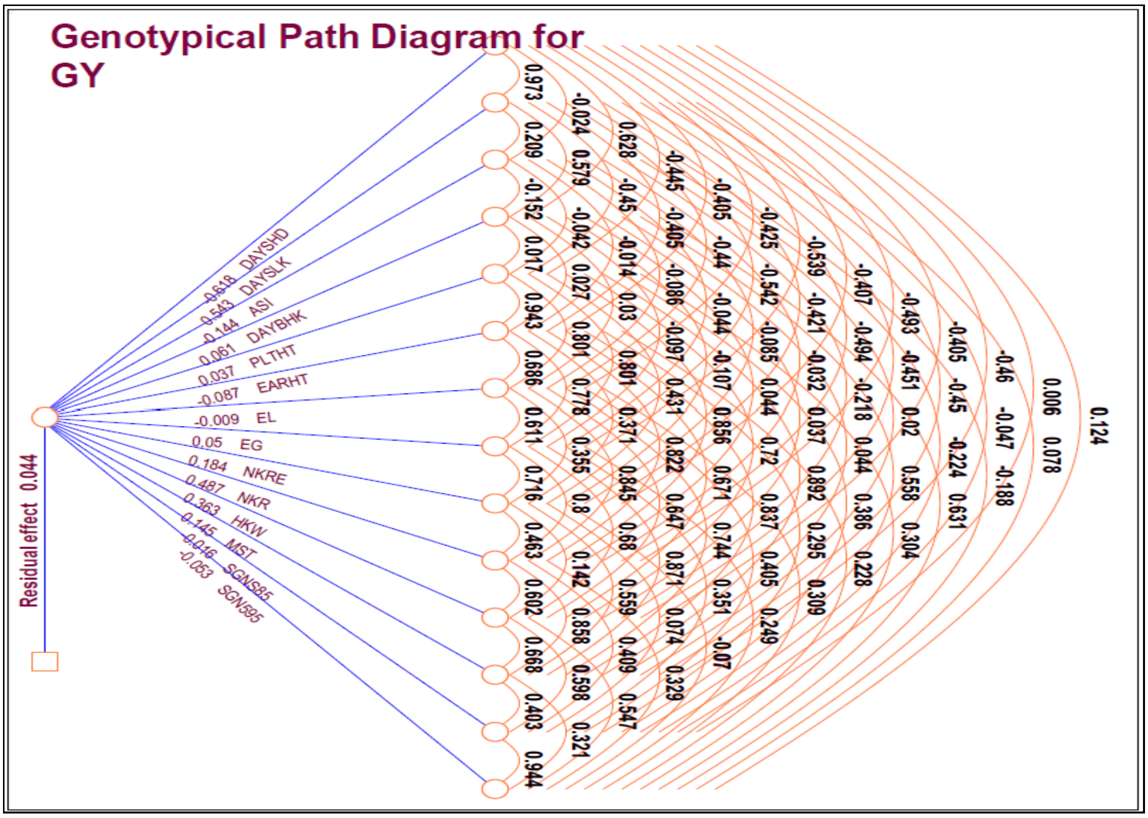

Fig. 2. Genotypic path diagram for grain yield and its component traits in maize (pooled over 11 environments)

3.6 Residual Effect

The residual effect obtained from the path coefficient analysis was 0.307 at the phenotypic level and 0.044 at the genotypic level (Figures 1 and 2, respectively). The relatively low residual effects indicate that the traits included in the analysis adequately explained the variation in grain yield. The coefficient of determination (R^2) showed that approximately 90.59% of the phenotypic variation and 99.81% of the genotypic variation in grain yield were accounted for by the fourteen component traits considered in the study, leaving only 9.41% and 0.19% of the variation, respectively, to other uncontrolled factors. The markedly lower residual effect at the genotypic level indicates that the selected traits explained the inherent genetic variation in grain yield more effectively than the corresponding phenotypic variation, which was partly influenced by environmental factors. Collectively, these findings confirm that the evaluated yield components accounted for most of the variation in grain yield and therefore represent reliable selection criteria for improving grain productivity in tropical maize hybrids.

4. Conclusion

The present investigation demonstrated the existence of substantial genetic variability and significant genotype × environment interactions among tropical maize hybrids, highlighting the importance of multi-environment evaluation for identifying superior and stable genotypes. Correlation analysis revealed that grain yield was positively associated with ear girth, number of kernels per row, ear length, plant height, hundred-kernel weight and number of kernel rows per ear, while flowering traits exhibited negative associations with grain yield. Genotypic correlations were generally higher than phenotypic correlations, indicating that these relationships were predominantly governed by genetic factors. Path coefficient analysis further established that number of kernels per row, hundred-kernel weight, ear girth and number of kernel rows per ear exerted the greatest positive direct effects on grain yield, identifying them as the most reliable selection criteria for yield improvement. The low residual effects obtained in the path analysis confirmed that the evaluated traits adequately explained the variation in grain yield. Overall, the findings indicate that simultaneous selection for number of kernels per row, hundred-kernel weight, ear girth and kernel rows per ear would constitute an efficient breeding strategy for developing high-yielding and widely adapted tropical maize hybrids.

5. Limitations

The study was conducted during one cropping season, although the material was evaluated across eleven environments. Detailed environmental characteristics and genotype-specific means were not presented. Strong intercorrelations among predictors may have influenced the stability of path coefficients, and multicollinearity diagnostics were not reported. The identified selection traits were not validated in an independent population.

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Declaration of AI Use

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Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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