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DISSECTION OF GENETIC VARIABILITY AND YIELD-ASSOCIATED TRAITS IN MAIZE HYBRIDS UNDER RAINFED CONDITIONS USING MULTIVARIATE ANALYSIS

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ABSTRACT
A field experiment was conducted during *Kharif*, 2024 under rainfed conditions in Telangana to evaluate phenological, morphological, and yield traits of 20 pre-release maize (*Zea mays* L.) hybrids along with 8 commercial checks. Analysis of variance revealed significant differences for ear height and grain yield, indicating substantial genetic variability and scope for selection under moisture stress. Early flowering hybrids such as BAUMH 22-2, BIO 9862, and RCRMH series were better adapted to short-duration conditions. High-yielding hybrids including BH 417189, GH 22336, RCRMH 23, and AHD 2035 showed superior performance with desirable agronomic traits and higher shelling percentage. Principal component analysis (PCA) identified seven components explaining 100% of total variation. The first three components accounted for 77.8% of the variance. PC1 (40.7%) was associated with grain yield, plant height, and ear height, representing the productivity axis. PC2 (23.6%) was related to phenological traits such as days to pollen shed, silking, and maturity, while PC3 (13.5%) was influenced by shelling percentage. The results indicate that yield and phenological traits are key contributors to genetic divergence and can be effectively utilized for selecting superior hybrids for rainfed environments

KEYWORDS: Genetic variability, Maize hybrids, Principal component analysis, Rainfed conditions, Yield

INTRODUCTION
Maize (*Zea mays* L.) is one of the most important cereal crops cultivated worldwide due to its wide adaptability and high yield potential. It is often referred to as the "queen of cereals" because of its superior productivity. In India, maize is grown over approximately 11.2 million hectares with a production of about 43.4 million tonnes during 2024–25. In Telangana, maize has become a major crop under rainfed conditions, covering nearly 5.79 lakh hectares with a production of about 33.92 lakh tonnes (https://upag.gov.in). Key maize-growing districts include Nirmal, Nagar Kurnool, Bhadradri Kothagudem, Khammam, and Jagtial. Maize serves as a vital raw material for poultry feed, livestock industries, and agro-processing sectors such as starch and ethanol production. The increasing demand from poultry and biofuel industries has further enhanced its importance. Moreover, maize requires relatively less water compared to other cereals like rice, making it suitable for rainfed ecosystems. However, maize production in rainfed areas is constrained by erratic rainfall, drought, and high temperature stress. Moisture stress during flowering and grain filling stages can reduce yield significantly, up to 30–40 per cent (Singh *et al.*, 2020). Additional challenges include declining soil fertility, pest incidence such as fall armyworm, and lack of location-specific hybrids. Recent studies emphasize the importance of genotype × environment interaction and multi-trait selection approaches in improving maize under stress conditions. For example, Singamsetti *et al.* (2023) reported that multi-trait index-based selection enhances genetic gain under moisture stress. Similarly, Manigben *et al.* (2024) highlighted the importance of combining ability and testcross evaluation in identifying drought-tolerant hybrids.

Advances in breeding technologies such as marker-assisted selection and genomic approaches have further accelerated progress. Rasheed *et al.* (2023) demonstrated that molecular tools improve selection efficiency, while Menkir *et al.* (2024) reported progress in developing climate-resilient maize hybrids. Additionally, physiological traits such as root architecture and water-use efficiency play a significant role in drought tolerance, as highlighted by Pati *et al.* (2025).Heat stress, often combined with moisture stress, further limits maize productivity. Therefore, developing hybrids with tolerance to multiple stresses is essential. Studies indicate that simultaneous improvement of yield and stress tolerance is achievable through targeted breeding strategies. Since hybrid performance varies across environments, evaluation under specific agro-ecological conditions is necessary. Therefore, the present study was undertaken to assess genetic variability and identify superior maize hybrids suitable for rainfed conditions in Telangana.

MATERIALS AND METHODS

The experiment was conducted during *Kharif,* 2024 under rainfed conditions at ARS, Karimnagar (18.439°N latitude, 79.128°E longitude, 259 m above mean sea level). The soil type was sandy loam. The weather conditions during the crop growth period from June to October, 2024 were generally favorable for maize cultivation under rainfed conditions. The mean maximum temperature ranged from 32.5°C to 38.5°C, with an overall average of 34.14°C, while the mean minimum temperature ranged from 24.3°C to 28.2°C, averaging 25.92°C. Relative humidity during the morning (RH-I) varied from 73.9% to 87.6% with an average of 84.34%, whereas afternoon relative humidity (RH-II) ranged from 58.9% to 79.0% with a mean of 73.00%. The normal rainfall received during the cropping season was 974.0 mm, while the actual rainfall recorded was 794.4 mm, indicating an overall deficit of 18.4% compared to the normal rainfall. A total of 53 rainy days were recorded during the season. Monthly rainfall deviation ranged from -30.2% in June to +22.0% in October (Table 1). Despite the deficit rainfall during most of the growing period, the distribution of rainfall across 53 rainy days helped sustain crop growth under rainfed conditions. A total of 28 maize hybrids (20 pre-release and 8 checks) was evaluated in a randomized block design in 3 replications. Each plot consisted of six rows of 4 m length, with spacing of 60 cm × 20 cm. The crop was grown entirely under rainfed conditions without irrigation. Recommended agronomic practices were followed uniformly.

Observations were recorded on five randomly selected plants per plot for traits including days to 50% pollen shedding, days to 50% silking, plant height, ear height, grain yield, and shelling percentage. Statistical analysis was carried out using analysis of variance (ANOVA) as described by Panse and Sukhatme (1961), and principal component analysis was performed using R software.

RESULTS AND DISCUSSIONS

The analysis of variance revealed significant differences among hybrids for grain yield and ear height, indicating the presence of genetic variability. Early flowering hybrids such as BAUMH 22-2 and BIO 9862 reached 50% pollen shedding and silking within 49–52 days. Other hybrids including AHD 8721, AHD 8722, RCRMH 20, and RCRMH 23 also exhibited early flowering (50–53 days). Early maturity is beneficial under rainfed conditions as it helps escape terminal drought stress, as reported by Kumar *et al.* (2023) and Smith *et al.* (2024). Most hybrids reached maturity within 92–94 days, confirming their suitability for short-duration environments, which is in agreement with findings of Amzeri *et al.* (2023) and Özata *et al.* (2026).

Plant height ranged from 145 cm to 159 cm, while ear height varied between 46 cm and 61 cm. Taller genotypes such as RCRMH 23 and LG 34.05 showed vigorous growth. Lower ear height observed in BAUMH 22-2 and BIO 9862 indicates compact plant architecture. These observations are consistent with findings reported by Teodoro *et al.* (2024) and Zhang *et al.* (2024).

Significant variation in grain yield was observed among hybrids. BH 417189 recorded the highest yield (6200 kg/ha), followed by GH 22336 (6000 kg/ha), RCRMH 23 (5900 kg/ha), and AHD 2035 (5700 kg/ha). Several hybrids performed above the mean yield of 5.1 t/ha. These results are supported by Ma *et al.* (2024) and Bougma *et al.* (2024), who emphasized the role of genotype × environment interaction in yield performance.

Shelling percentage ranged from 72.1% to 76.1%, with BAUMH 22-2 recording the highest value. Hybrids such as BH 417189 and GH 22336 showed better grain recovery efficiency. Similar findings were reported by Xiang *et al.* (2024).

The analysis of variance revealed significant differences among hybrids for grain yield and ear height, indicating the existence of substantial genetic variability among the evaluated materials. The presence of variability is a prerequisite for effective selection and genetic improvement in maize breeding programmes. Early flowering hybrids such as BAUMH 22-2 and BIO 9862 reached 50% pollen shedding and silking within 49–52 days, while AHD 8721, AHD 8722, RCRMH 20, and RCRMH 23 also exhibited early flowering (50–53 days). Early flowering and maturity are important adaptive mechanisms under rainfed environments because they enable plants to complete their life cycle before the onset of terminal moisture stress. Such drought escape mechanisms reduce exposure of reproductive stages to water deficit conditions, thereby minimizing yield losses. Therefore, these hybrids may serve as valuable genetic resources for developing short-duration maize cultivars suitable for moisture-limited environments. Similar observations were reported by Kumar et al. (2023) and Smith et al. (2024), who emphasized the importance of early maturity for enhancing yield stability under drought-prone conditions. Most hybrids attained physiological maturity within 92–94 days, indicating their suitability for short-duration production systems and rainfed agro-ecosystems, in agreement with the findings of Amzeri et al. (2023) and Özata et al. (2026).

Plant height ranged from 145 cm to 159 cm, while ear height varied from 46 cm to 61 cm. Taller genotypes such as RCRMH 23 and LG 34.05 exhibited vigorous vegetative growth, which may contribute to increased photosynthetic capacity and biomass accumulation. Conversely, lower ear placement observed in BAUMH 22-2 and BIO 9862 reflects a compact plant architecture that is generally associated with improved lodging resistance and efficient assimilate partitioning. Ear height is an important agronomic trait because moderate ear placement facilitates mechanical harvesting and enhances plant stability under adverse environmental conditions. The significant variation observed for ear height suggests opportunities for selecting genotypes with desirable plant architecture. These findings are consistent with those reported by Teodoro et al. (2024) and Zhang et al. (2024), who demonstrated the importance of plant architectural traits in determining maize productivity and adaptation.

Significant variation in grain yield was observed among hybrids, reflecting differences in their genetic potential and adaptation to rainfed conditions. BH 417189 recorded the highest grain yield (6200 kg ha^{-1}), followed by GH 22336 (6000 kg ha^{-1}), RCRMH 23 (5900 kg ha^{-1}), and AHD 2035 (5700 kg ha^{-1}). These hybrids consistently outperformed the overall mean yield of 5100 kg ha^{-1}, indicating superior adaptation and efficient utilization of available soil moisture under rainfed conditions. The superior performance of these hybrids may be attributed to their favourable combination of phenological traits, plant architecture and grain filling ability. From a breeding perspective, these hybrids represent promising candidates for multilocation testing and may serve as potential parental materials in future hybrid development programmes aimed at improving productivity under moisture-limited environments. Similar observations were reported by Ma et al. (2024) and Bougma et al. (2024), who highlighted the importance of genotype × environment interactions in determining hybrid performance and yield stability.

Shelling percentage ranged from 72.1% to 76.1%, with BAUMH 22-2 recording the highest value (76.1%), followed closely by RCRMH 23 (76.0%) and GH 22336 (75.8%). Shelling percentage is an economically important trait because it directly influences grain recovery and marketable yield. Higher shelling percentage reflects efficient grain development and better partitioning of assimilates towards kernels, ultimately contributing to enhanced productivity. The superior shelling efficiency observed in BH 417189, GH 22336 and RCRMH 23 further strengthens their suitability for commercial cultivation. These hybrids combine desirable grain yield with efficient grain recovery, making them valuable candidates for breeding programmes targeting both productivity and profitability. Similar findings were reported by Xiang et al. (2024), who identified shelling percentage as an important contributor to grain yield improvement in maize.

Overall, the observed variation in flowering behaviour, plant architecture, grain yield and shelling percentage demonstrates the existence of considerable genetic diversity among the evaluated hybrids. The superior performance of BH 417189, GH 22336, RCRMH 23 and AHD 2035 under rainfed conditions suggests that these hybrids possess desirable adaptive traits that can be exploited in breeding programmes for developing climate-resilient maize cultivars. The results further indicate that simultaneous selection for early maturity, favourable plant architecture, higher shelling percentage and grain yield could accelerate the development of high-yielding maize hybrids adapted to rainfed agro-ecological regions of Telangana.

Although ANOVA revealed significant differences only for grain yield and ear height, all traits were included in Principal component analysis because multivariate analyses evaluate the combined contribution of correlated variables to total genetic variability. Therefore, PCA provides a comprehensive assessment of genetic divergence among hybrids beyond the significance of individual traits. The use of PCA for all measured traits is a standard practice in maize diversity studies because traits with low individual variation may still contribute substantially to multivariate discrimination among genotypes

Principal component analysis

Principal component analysis (PCA) was employed to determine the relative contribution of various agronomic traits towards genetic variability among the maize hybrids evaluated under rainfed conditions. The first three principal components explained 83.90% of the total variation, indicating that these components effectively captured the majority of variability present among the hybrids. Similar observations have been reported in maize by Mohan et al. (2022) and Singh et al. (2024), who reported that the first few principal components account for most of the variability among genotypes.

The first principal component (PC1) accounted for 45.89% of the total variation and exhibited positive loadings for days to 50% silking (0.460), plant height (0.394), days to 75% maturity (0.390), ear height (0.386) and grain yield (0.377). The strong association of grain yield with plant height and ear height indicates that these traits contributed substantially to productivity-related variation among the hybrids. Similar results were reported by Mohan et al. (2022), Singh et al. (2024) and Teodoro et al. (2024), who observed that yield and plant architectural traits are major determinants of genetic divergence in maize.

The second principal component (PC2) explained 26.41% of the total variation and was characterized by positive loadings for days to 50% pollen shed (0.480), days to 75% maturity (0.384) and days to 50% silking (0.349), whereas plant height (-0.375) and ear height (-0.448) showed negative loadings. These results indicate that flowering and maturity traits contributed significantly to the discrimination of genotypes and reflected adaptation differences under rainfed conditions. Similar findings were reported by Sathya Sheela et al. (2023), who demonstrated that phenological traits contribute substantially to variability among maize genotypes grown under diverse environments.

The third principal component (PC3) contributed 11.60% of the total variation and was predominantly associated with shelling percentage (0.802). The high loading value suggests that shelling percentage independently contributed to genetic divergence among the evaluated hybrids. Comparable results were reported by Borkhatariya et al. (2023), who identified shelling percentage as an important trait contributing to diversity among maize genotypes.

PCA Biplot

The PCA biplot revealed the association between hybrids and measured traits. Grain yield, plant height and ear height vectors were oriented in the same direction, indicating a positive correlation among these traits. Similar relationships between grain yield and plant architecture have been reported by Teodoro et al. (2024) and Zhang et al. (2024). Hybrids BH 417189, GH 22336, RCRMH 23, RCRMH 20 and AHD 2035 were located in the positive quadrant of PC1 and were closely associated with grain yield and growth-related traits, indicating their

superior performance under rainfed conditions. Among these, BH 417189 recorded the highest grain yield (6200 kg ha^{-1}), followed by GH 22336 (6000 kg ha^{-1}) and RCRMH 23 (5900 kg ha^{-1}), suggesting their suitability for cultivation under moisture-limited environments.

Flowering and maturity traits were strongly associated with PC2. Hybrids AHD 2035, JH 20088 and BH 418103 showed positive association with these traits and exhibited relatively later maturity. In contrast, BAUMH 22-2, BIO 9862 and Bio 605 were positioned away from the productivity axis and were associated with early flowering behaviour. Early maturity has been recognized as an important drought escape mechanism under rainfed environments (Kumar et al., 2023; Smith et al., 2024).

The broad dispersion of hybrids across different quadrants of the biplot indicated the existence of substantial genetic variability among the evaluated materials. Similar observations were reported by Singh et al. (2024) and Borkhatariya et al. (2023), who emphasized that wide distribution of genotypes in PCA space reflects greater genetic divergence and provides opportunities for effective parent selection. Therefore, the superior hybrids identified in the present study, particularly BH 417189, GH 22336, RCRMH 23 and AHD 2035, may serve as valuable genetic resources for developing high-yielding maize hybrids adapted to rainfed conditions.

Overall, the PCA results demonstrated that grain yield, flowering behaviour, plant height, ear height and shelling percentage were the major contributors to genetic variability. These traits can therefore be effectively utilized as selection criteria in maize breeding programmes aimed at improving productivity and adaptation under rainfed environments.

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Authorship & Contributor ship

Authors' contributions: SD conducted the complete research process, including drafting and preparing the initial and final version of the manuscript. UG, MP , BD and VBA were involved in the research methodology, manuscript creation and editing. MVN involved in overall supervision from research to manuscript preparation. All authors read and approved the final manuscript.

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Table :1 Temperature, Relative Humidity and Rainfall information at ARS, Karimnagar

S. No.	Month	Max. Temp. (^{0}C)	Min. Temp. (^{0}C)	R.H-I (%)	R.H-II (%)	Normal rainfall (mm)	Actual rainfall (mm) &	Rainy days	Deviation (%)
1	June, 2024	38.5	27.0	73.9	58.9	159.1	111.0	7	-30.2
2	July, 2024	32.5	24.9	87.2	72.9	310.7	238.4	21	-23.3
3	August, 2024	33.1	28.2	87.6	78.4	198.3	151.5	11	-23.6
4	September, 2024	32.9	25.2	86.8	79.0	239.5	212.5	7	-11.3
5	October, 2024	33.7	24.3	86.2	75.8	66.4	81.0	7	+22.0
	Average	34.14	25.92	84.34	73	974	794.4	53	-18.4

Table:2 Analysis of Variance (ANOVA) for Different Traits in Maize Hybrids

Source of Variation	df	Grain Yield(kg/ha)	Shelling percentage	Days to 50% Pollen shed	Days to 50% silking	Days to 75% Dryhusk	Plant height (cm)	Ear height(cm)
Replications	2	546219.37	3.24	5.15	8.82	9.08	96.46	40.96
Treatments (Entries)	27	938300.88*	3.21	1.49	0.97	1.34	30.72	43.61*
Error	54	461525.71	3.07	1.04	0.97	0.94	21.44	23.87
Total	83							

Significant at P ≤ 0.05; ** Significant at P ≤ 0.01; NS = Non-significant.

Table 3: Mean performance of maize hybrids for yield and its contributing characters under rainfed conditions during *Kharif,* 2024

S.No	Name of the hybrid	Days to 50% pollen shed	Days to 50% silking	Days to 75% maturity	Plant height (cm)	Ear height (cm)	Shelling percentage	Grain Yield kg/ha
1	AH 4724	51	53	93	151	51	73.0	4300
2	AHD 2035	52	54	93	152	55	75.0	5700

3	AHD 2109	51	53	93	153	51	73.9	5400
4	AHD 2130	51	54	94	153	49	73.4	4500
5	AHD 8721	50	53	92	159	61	74.8	5100
6	AHD 8722	50	53	93	153	54	74.3	4300
7	BAUMH 22-2	49	52	92	145	46	76.1	4200
8	BH 417144	50	53	92	155	55	74.9	5300
9	BH 417189	51	54	94	156	58	75.6	6200
10	BH 418103	51	54	94	151	54	75.5	5000
11	BH 419500	51	53	93	152	52	74.9	5200
12	CMH 19015	50	53	93	152	52	75.4	4600
13	EH 3907	51	53	94	154	52	75.1	4800
14	EH 3926	50	53	93	152	52	75.0	4700
15	FH 4154	50	53	93	155	58	73.7	4800
16	GH 20113	51	53	93	154	55	75.5	5600
17	GH 22336	50	53	93	152	55	75.8	6000
18	JH 20088	51	54	94	152	51	75.3	5500
19	RCRMH 20	50	53	93	159	60	75.3	5500
20	RCRMH 23	50	53	93	157	58	76.0	5900
21	BIO 9544 (C)	51	53	93	150	48	72.1	5400
22	BIO 9862 (C)	49	52	92	149	47	73.1	4700
23	Bio 605 (C)	50	52	92	148	49	72.8	4100
24	CMH 8 292 (C)	49	52	93	155	56	75.2	4700
25	CP 858 (C)	51	54	94	153	55	75.2	4700
26	DKC 7074 (C)	50	53	93	153	51	75.0	5300
27	LG 34.05 (C)	51	54	94	158	56	74.9	5100
28	NK 6240 (C)	51	54	94	152	53	74.3	4800
	Location Mean	50	53	93	153	53	74.7	5100
	CV(%)	2.05	1.88	1.06	2.75	8.74	2.34	13.18
	F(Prob)	0.15	0.51	0.21	0.04	0.02	0.42	0.011
	CD(5%)	1.7	1.63	1.62	6.89	7.64	2.86	1.09

Table 4. PCA loading matrix showing the contribution of different traits to principal components in maize hybrids

S. No.	Name of the hybrid	PC 1	PC 2	PC 3
1	Days to 50% pollen shed	0.356	0.480	-0.128
2	Days to 50% silking	0.460	0.349	0.027
3	Days to 75% maturity	0.390	0.384	0.160
4	Plant height (cm)	0.394	-0.375	-0.456
5	Ear height (cm)	0.386	-0.448	-0.288
6	Shelling percentage	0.253	-0.347	0.802
7	Grain Yield (kg/ha)	0.377	-0.195	0.155

Table 5: Eigenvalues, Percentage Variance, and Cumulative Variance Explained by Principal Components in maize hybrids as per PCA Loading Matrix

Principal Component	Eigenvalue	% Variance	Cumulative %
PC1	3.212	45.89	45.89
PC2	1.849	26.41	72.30
PC3	0.812	11.60	83.90
PC4	0.650	9.28	93.18
PC5	0.257	3.67	96.85
PC6	0.128	1.83	98.68
PC7	0.091	1.30	100

Fig 1: PCA

Biplot of Maize hybrids evaluated under Rainfed conditions

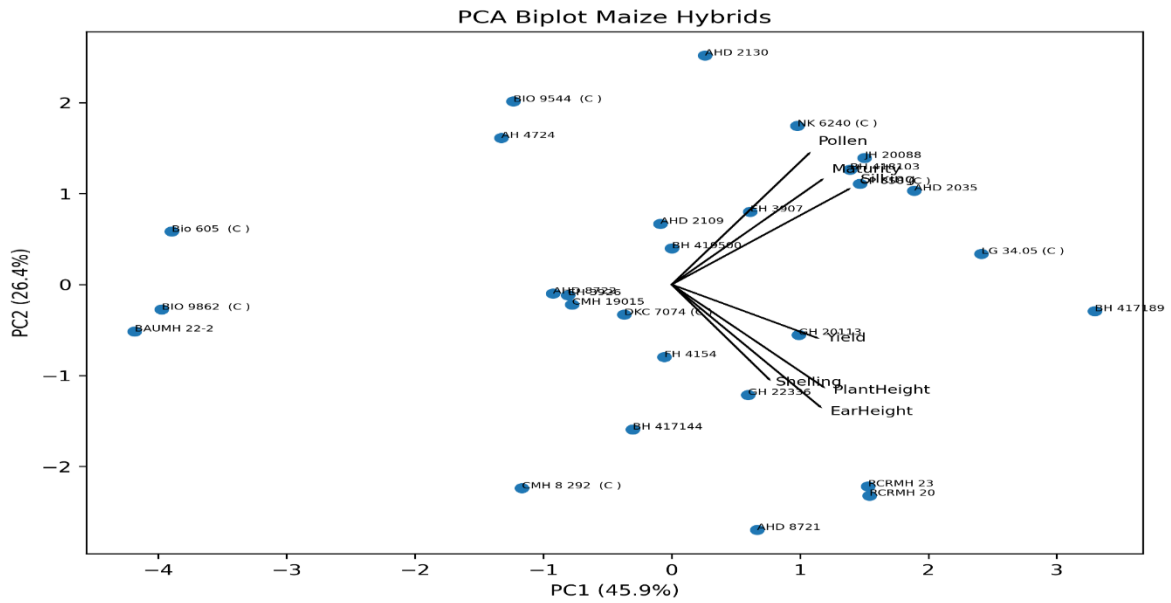


Fig 2: Scree Plot Showing Variance Explained by Principal Components
Scree plot of principal components
Percentage variance explained by each principal component in maize hybrids under rainfed conditions.

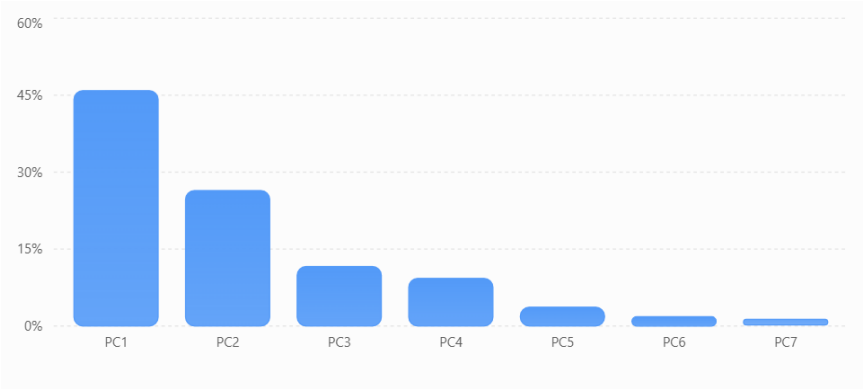


Fig 3: Cumulative Contribution of Principal Components to Total Variability

