Genetic Variability, Multivariate Analysis and Identification of Yield-Contributing Traits in Okra (Abelmoschus esculentus L. Moench)

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ABSTRACT

Okra is an important vegetable crop in tropical, subtropical, and temperate region of the world. Yet, productivity remains strongly influenced by genotype and seasonal environment. This study evaluated the extent of genetic variability and trait relationships among eight okra genotypes grown during the Kharif season (March–June 2025) under AEZ-14 conditions. The experiment followed a Randomized Complete Block Design with three replications. Observations were recorded for phenological, vegetative, and yield-related traits, followed by analyses of variance, genetic parameters, and principal component analysis. Significant differences were observed for all characters, confirming substantial variability among genotypes. Days to first flowering ranged from 30.33 to 34.00 days, while fruit yield per plant varied widely from 128.93 g to 230.08 g. The highest yield was obtained from OLR-3 (230.08 g), followed by Century and Sobujsathi (210.33 g). Fruit length (10.57–17.30 cm), fruit diameter (1.23–2.13 cm), and single fruit weight (11.70–15.00 g) also exhibited marked variation. Phenotypic coefficients of variation exceeded genotypic values for all traits, indicating environmental influence, although moderate to high GCV was observed for fruit yield per plant (17.18), fruit length (15.75), and fruit number per plant (12.05). Broad-sense heritability was high for plant height (98%) and leaf number (83%), while fruit yield per plant showed moderate heritability (68%). Principal component analysis revealed that the first three components explained 81.9% of total variation, with PC1 alone accounting for 41.4% and strongly associated with yield and fruit traits. Genotypes positioned positively along PC1, particularly OLR-3 and Century, demonstrated superior yield potential. The findings highlight the presence of exploitable genetic variability and emphasize fruit yield per plant, fruit number, fruit length, and single fruit weight as key selection criteria for okra improvement under Bangladeshi conditions.

Keywords: Okra, Genetic variation, Genotype, Principal Component Analysis, Yield-contributing traits.

INTRODUCTION

Okra (*Abelmoschus esculentus* L. Moench) is an important vegetable crop widely cultivated in tropical and subtropical regions for its tender pods, nutritional value and broad adaptability. In Bangladesh, okra is grown almost year-round with an average yields ranging from 4.6 to over 5.7 t ha^{-1} (BBS, 2023). Okra grown in March to June constitutes a major production period and faces rising temperatures, increasing day length and variable humidity. These environmental conditions highly influence vegetative growth, flowering, fruit development and yield. It makes this season particularly suitable for evaluating genetic variability and trait relationships among okra genotypes under Bangladeshi field conditions (Anand *et al.*, 2025).

Assessment and exploitation of genetic variability are fundamental to crop improvement and commercial cultivation, which determine the effectiveness of selection and the magnitude of genetic gain. In okra, yield and

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its component traits are quantitatively inherited which are strongly influenced by environmental factors. So, partitioning phenotypic variation into genetic and environmental components using variability estimates is essential for identifying traits suitable for selection under specific seasonal conditions. Genetic parameters such as phenotypic and genotypic coefficients of variation, heritability in the broad sense (h^2bs) and genetic advance are usually used to quantify total variability for distinguishing genetic effects from environmental influences. Although heritability indicates the degree of genetic control over trait expression. Heritability does not independently predict selection response. When interpreted together, heritability and genetic advance provide a more reliable estimate of expected genetic gain and assist in identifying traits predominantly governed by additive gene action (Kumar *et al.*, 2020; Kumar *et al.*, 2013; Kumar *et al.*, 2019). Adequate genetic variability is therefore a prerequisite for effective selection-based breeding. As a result these parameters support identification of superior genotypes, assessment of genetic diversity, selection of suitable parents in molecular and biochemical approaches for crop improvement (Bello *et al.*, 2014; Olawuyi *et al.*, 2015; Temam *et al.*, 2020).

Principal component analysis (PCA) is a robust multivariate statistical tool used to reduce data dimensionality for identifying traits contributing to overall genetic variation. While correlation analysis is commonly applied to estimate relationships among individual traits and yield (Yücel, 2004; Kumar & Paul, 2016; Polat *et al.*, 2020), correlation coefficients is unable to adequately capture complex multivariate interactions (Nbeaa *et al.*, 2023). Whereas, PCA overcomes this limitation by transforming correlated variables into a smaller number of orthogonal principal components, which enhance interpretation of trait interrelationships, facilitating genotype classification based on combined performance and identification of major sources of variation (Abdalla *et al.*, 2025; Moralista & Rueda, 2023). PCA method is based on eigenvalues and eigenvectors, which quantify the magnitude and direction of variation and help to prioritize key traits for breeding strategies (Mishra *et al.*, 2017; Abhilash *et al.*, 2023). For this reason, PCA has therefore been widely applied in crop improvement studies to assess genetic diversity, explain relationships among economically important traits and support germplasm evaluation and parent selection for development of efficient selection indices (Ziaf *et al.*, 2016; Saleem *et al.*, 2023; Bukola *et al.*, 2025).

The present study was carried out to assess genetic variability and principal component analysis among okra genotypes with the objective of identifying important traits and superior genotypes for the development of high-yielding, seasonally adapted okra varieties.

MATERIALS AND METHODS

Experimental site

The experiment was conducted at the research field of Gopalganj Science and Technology University, Bangladesh during Kharif season (March to June) in 2025. Soils of the experimental field was peat and non-calcareous dark grey floodplain soils of AEZ-14 (Gopalganj–Khulna Bils) with high organic matter, very strongly acidic to neutral topsoil reaction (Ahmmed *et al.*, 2018).

Experimental material and design

The experimental material for the present study comprised of eight genotypes that include four high yielding varieties (Century, Superstar, Sobujsathi, BARI Dherosh-1) and four local varieties (Borni, OLR-1, OLR-2 and OLR-3). Seeds of the varieties were collected from national research institution, local seed markets and nationally registered seed companies (Table 1). The varieties were evaluated through a field experiment conducted in a Randomized Complete Block Design (RCBD) with three replications.

Each variety was raised in a single plot of 4×4 square feet maintaining a plant spacing of 1×1 square feet. Two to three seeds per hill were dibbled at 60 cm between rows and 30 cm among plants. A distance of 2 feet in the form of drain was maintained between the block and between the plots within a block.

Varieties were randomly assigned in different blocks. The fertilizer and manure were applied as per recommended dose for the commercial cultivation of okra and the cultural practice were followed when required.

Observation recorded

Observations were recorded on ten randomly selected plants from each variety in each replication for traits namely days to first flowering, days to first fruiting, plant height (cm), leaf number, number of nodes, internode length (cm), fruit number per plant, fruit length (cm), fruit diameter (cm), single fruit weight (g), fruit yield per plant (g).

Table 1. List of the okra genotype used for the study

Okra genotype	Varietal feature
Century	High yielding, popular among farmers
Superstar	High yielding variety, widely cultivated
Sobujsathi	High yielding, tender pods.
BARI Dherosh-1	High yielding variety, widely cultivated
Borni	Local land race, low input
OLR-1	Local land race, low input
OLR-2	Local land race, low input
OLR-3	Local land race, low input

BARI – Bangladesh Agricultural Research Institute, OLR – Okra Land Race

Statistical analysis

The collected data were evaluated for significance using analysis of variance (ANOVA) followed by the least significant difference (LSD) test at the $P < 0.05$ level (Freeman *et al.*, 1985). To test the differences between genotypes, Duncan's Multiple Range Test (DMRT) was performed according to the method of (Heinisch *et al.*, 1962). Statistical analyses for genetic variability, was conducted using MSTAT-C (Statistical analysis software). The variance components namely phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), broad sense heritability and genetic advance were determined following Kumar & Misra (1985) and Kute *et al.*, (2023). According to Abhilash *et al.*, (2023) and Lever *et al.*, (2017), mean data for each character along with variety was subjected to multivariate Principal Component Analysis (PCA) and scattered diagram obtained for principal component scores were using Minitab 18 computer package programs. Principal component analysis (PCA) was performed on standardized quantitative trait data (mean = 0, variance = 1) using the correlation matrix to assess multivariate variation among eight okra genotypes according to Turbay *et al.*, (2024). Eigenvalues, proportion of variance, cumulative variance, and eigenvectors were extracted. Principal components with eigenvalues ≥ 1 were considered significant according to Kaiser's criterion according to Alemu & Mohammed, (2022). A scree plot was constructed to visualize component retention, and a PCA biplot based on the first two principal components was generated to interpret trait associations and genotype dispersion.

RESULT AND DISCUSSION

Mean performance of okra varieties for yield and yield-contributing traits

The analysis of variance revealed significant differences among the eight okra varieties for all studied characters, indicating the presence of considerable genetic variability under the agro-ecological conditions of AEZ-14. The mean performance of varieties for flowering, vegetative growth, yield components, and fruit yield per plant varied (Table 2).

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Days to first flowering ranged from 30.33 to 34.00 days with an average of 32 days. Borni was the earliest to flower (30.33 days), followed by OLR-2 (31.00 days) and OLR-1 (31.33 days), whereas Century required the longest period (34.00 days). Days to first fruiting varied from 32.67 to 38.33 days with an average of 35.17 days. OLR-1 was the earliest to fruit (32.67 days), while Borni was the latest (38.33 days). Plant height ranged from 146.33 to 174.91 cm with an average of 165.25 cm. The tallest plants were recorded in Sobujsathi (174.91 cm) and OLR-2 (173.26 cm), whereas Borni produced comparatively shorter plants (146.33 cm). Leaf number ranged from 17 to 24 with an average of 20.88. Borni (24 leaves) and OLR-3 (23 leaves) produced more leaves, while OLR-1 had the fewest (17 leaves). Number of nodes ranged from 18.33 to 26.33 with an average of 22.75. Highest number of nodes recorded in Sobujsathi (26.33) and lowest number in Superstar (18.33). Fruit number per plant showed marked variation ranged from 11.00 to 16.00 with an average of 13.88. The highest fruit number per plant were recorded in Sobujsathi and OLR-3 (16.00), closely followed by OLR-1 (15.67). Fruit length ranged from 10.57 to 17.30 cm, with an average of 13.96 cm. Century (17.30 cm) and OLR-2 (17.14 cm) produced longer fruits, while Borni produced the shortest fruits. Fruit diameter varied from 1.23 to 2.13 cm with an average of 1.60 cm. Century recorded the maximum diameter (2.13 cm) and minimum in Superstar (1.23 cm). Single fruit weight ranged from 11.70 g to 15.00 g with an average of 13.23 gm. The highest single fruit weight recorded in Century (15.00 g) and lowest in Borni (11.70 g). Fruit yield per plant differed significantly among varieties, ranging from 128.93 g to 230.08 g with an average of 184.15 g. The highest yield was obtained from OLR-3 (230.08 g), followed by Century and Sobujsathi (both 210.33 g), whereas Borni produced the lowest yield (128.93 g).

The mean performance of phenological, vegetative, and yield-related parameters varied significantly between genotypes. Early flowering and fruiting in Borni and OLR-1 indicates that they might be suitable for cropping systems with short growing seasons. However, okra yield is determined by a complex combination of fruit size, fruit number, and biomass accumulation rather than phenology alone. This is demonstrated by the fact that early flowering alone did not translate into better yield; similar results were reported earlier (Reddy *et al.*, 2013), (Saleem *et al.*, 2018). In OLR-3, Century, and Sobujsathi, high fruit yield per plant was mostly linked to advantageous combinations of fruit weight, length, diameter, and quantity of fruits per plant. This demonstrates that okra's higher yield performance is not dependent on the dominance of a single yield-contributing trait but rather on the cumulative effects of several traits (Abdela *et al.*, 2022). Borni, on the other hand, produced more leaves with a lower yield, which is explained by the reduced size and weight of its fruits. Variations in plant architecture reflect inherent genetic differences among the varieties and influence assimilate production and partitioning This emphasizes that excessive vegetative growth does not always result in increased production, which reported in different findings (Kute *et al.*, 2023; Reddy *et al.*, 2022; Awasthi *et al.*, 2022; Vani *et al.*, 2021). From the findings of the present suggest that both released varieties and local lines possess valuable traits that can be exploited either directly for cultivation or as parents in future okra improvement programs under Bangladeshi conditions.

Table 2. Mean performance of okra genotype based on yield and yield contributing characters

Genotye	Days to first flowering (d)	Days to first fruiting (d)	Plant height (cm)	Leaf number (No.)	Number of nodes (No.)	Fruit number per plant (No.)	Fruit length (cm.)	Fruit diameter (Cm.)	Single fruit weight (g)	Fruit yield per plant (g)
Century	34.00^{a}	33.00^{de}	170.75^{c}	22^{bc}	20.67^{c}	14.00^{b}	17.30^{a}	2.13^{a}	15.00^{a}	210.33^{ab}
Superstar	33.00^{ab}	34.67^{cde}	173.05^{b}	19^{d}	18.33^{c}	13.00^{b}	13.43^{b}	1.23^{d}	12.17^{de}	157.50^{c}
Sobujsathi	32.33^{bc}	37.00^{ab}	174.91^{a}	21^{c}	26.33^{a}	16.00^{a}	13.80^{b}	1.76^{b}	13.17^{cd}	210.33^{ab}

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BARI Dherosh-1	32.33^{bc}	36.00^{bc}	168.44^{d}	19^{d}	19.67^{c}	13.00^{b}	13.51^{b}	1.57^{bc}	12.75^{cde}	163.84^{c}
Borni	30.33^{e}	38.33^{a}	146.33^{g}	24^{a}	25.33^{a}	11.00^{c}	10.57^{c}	1.51^{bc}	11.70^{e}	128.93^{d}
OLR-1	31.33^{cde}	32.67^{e}	163.96^{e}	17^{e}	25.00^{ab}	15.67^{a}	11.02^{c}	1.59^{bc}	12.87^{cde}	201.20^{b}
OLR-2	31.00^{de}	35.00^{cd}	173.26^{ab}	22^{bc}	21.67^{bc}	12.33^{bc}	17.14^{a}	1.59^{bc}	13.77^{bc}	171.01^{c}
OLR-3	31.67^{cd}	34.67^{cde}	151.31^{f}	23^{ab}	25.00^{ab}	16.00^{a}	14.94^{b}	1.41^{cd}	14.38^{ab}	230.08^{a}
Mean	32.00	35.17	165.25	20.88	22.75	13.88	13.96	1.60	13.23	184.15
$LSD_{(0.05)}$	1.056	1.908	1.729	1.11	3.321	1.546	2.109	0.2605	1.148	23.25
SE(±)	0.413	0.676	3.81	0.833	1.07	0.66	0.875	0.093	0.392	12.038
SD	1.168	1.911	10.775	2.357	3.028	1.868	2.475	0.263	1.107	34.05
CV (%)	3.08	5.06	0.98	4.96	13.61	10.39	14.08	15.24	8.09	11.83

Values are expressed as mean. Mean with different letters within the same row differ significantly at $p \leq 0.05$.

Under the agro-ecological circumstances of AEZ-14, Bangladesh, the current study found significant genetic heterogeneity across the assessed okra genotypes for all examined variables. The existence of exploitable genetic variance, a crucial requirement for efficient selection and genetic development in okra, is confirmed by the substantial differences found by ANOVA. Similar findings of significant variation across okra genotypes have been widely documented, highlighting the quantitative character of yield and its constituent features as well as their susceptibility to environmental factors (Reddy *et al.*, 2022; Kute *et al.*, 2023).

Genetic variability: Genotypic and phenotypic variance

In the present study, the high PCV values (>20%) were observed in fruit length (21.13), fruit diameter (20.59), and fruit yield per plant (20.86) (Table 3). While, moderate PCV values (<10-20%) were observed for leaf number (11.99), number of nodes (17.34), fruit number per plant (15.91) and single fruit weight (10.66). Furthermore, low PCV values (<10%) were observed in days to first flowering (4.43), days to first fruiting (6.83) and plant height (6.57). For all traits studied, PCV values were higher than the corresponding GCV values. High GCV values (>20%) were not observed for the studied characters. While, moderate GCV values (<10-20%) were observed for leaf number (10.92), number of nodes (10.74), fruit number per plant (12.05), fruit length (15.75), fruit diameter (13.89) and fruit yield per plant (17.18). However, low GCV values (<10%) were observed in days to first flowering (3.19), days to first fruiting (4.58) and plant height (6.50) and single fruit weight (6.95).

The magnitude of phenotypic coefficient of variation (PCV) was higher than the corresponding genotypic coefficient of variation (GCV) for all traits, indicating that environmental effects contributed to the observed variability. However, the relatively low differences between PCV and GCV for traits such as fruit yield per plant, fruit length, fruit number per plant, and number of nodes indicate greater stability of these traits across environments, implying stronger genetic regulation and suggesting that direct phenotypic selection for these characters would be comparatively efficient and reliable in breeding programs as reported earlier by (Kumar *et al.*, 2020; Syfullah *et al.*, 2018; Reddy *et al.*, 2012). High PCV values observed for fruit yield per plant, fruit length, and fruit diameter indicate greater scope for selection and improvement. Moderate GCV estimates for

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fruit yield per plant and fruit length further support the presence of sufficient heritable variability, which is inconsistence with earlier report (Rambabu *et al.,* 2019; Chandramouli *et al.,* 2016; Vani *et al.,* 2021; Priyanka *et al.,* 2018). On the other hand, Low GCV and PCV estimates coupled with minimal variation for days to first flowering, days to first fruiting, and plant height indicate a narrow genetic base and limited scope for variability-driven improvement. Under such conditions, considerable improvement through conventional selection is less effective; instead, progress would depend on identifying superior phenotypes or introducing new allelic variation via hybridization or germplasm diversification, as the close relation between genotypic and phenotypic variation implies stable expression across different environment, as observed by (Kumar *et al.,* 2020; Reddy *et al.,* 2022; Kute *et al.,* 2023).

Table 3. Estimation of genetic parameters of okra genotypes based on yield and yield contributing characters

Characters	**Phenotypic variance** $(\delta^2 p)$	**Genotypic variance** $(\delta^2 g)$	**PCV (%)**	**GCV (%)**	**Heritability** $(h^2 b)$	**GA**	**GA (%)**
Days to first flowering (d)	2.01	1.04	4.43	3.19	52	0.73	2.29
Days to first fruiting (d)	5.76	2.60	6.83	4.58	45	0.12	0.35
Plant height (cm)	117.84	115.24	6.57	6.50	98	0.15	0.09
Leaf number (No.)	6.27	5.20	11.99	10.92	83	3.65	17.48
Number of nodes (No.)	15.56	5.97	17.34	10.74	38	11.92	52.40
Fruit number per plant (No.)	4.87	2.80	15.91	12.05	57	0.95	6.84
Fruit length (cm.)	8.71	4.84	21.13	15.75	56	0.28	2.02
Fruit diameter (cm.)	0.11	0.05	20.59	13.89	46	0.01	0.41
Single fruit weight (g)	1.99	0.84	10.66	6.95	42	0.00	0.01
Fruit yield per plant (g)	1475.55	1001.32	20.86	17.18	68	1.40	0.76

Here, $\delta^2 g$ = Genotypic variance, $\delta^2 p$ = Phenotypic variance, GCV = Genotypic coefficient of variance, PCV = Phenotypic coefficient of variance, $h^2 b$ = Heritability in broad sense, GA = Genetic advance, GA% = Genetic advance in percent of mean

Heritability (broad sense)

High Broad-sense heritability estimates (>70%) were observed for plant height (98) and leaf number (83) (Table 3). While, moderate genetic heritability (50-70%) were observed in days to first flowering (52), fruit number per plant (57), fruit length (56) and fruit yield per plant (68). Moreover lower heritability (<50%) were observed in days to first fruiting (45), number of nodes (38), fruit diameter (46) and single fruit weight (42). Although estimations of heritability explain the extent of genetic control over trait expression, it is necessary to analyze them along with genetic advance to determine how effective they are in selection decisions.

According to the current study, additive gene action plays a substantial role with high heritability and significant genetic advance as a percentage of the mean for the number of nodes, comparable with the observation noted earlier (Ranga *et al.,* 2021; Phundan Singh, 2017). Therefore, direct selection for this characteristic will be

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fruitful. There is a scope for improvement through selection, as evidenced by the modest genetic advance and moderate heritability seen for leaf number, align with previous report (Chetana *et al.*, 2021; Walling *et al.*, 2020).

Genetic advance (GA) and Genetic advance as a percent over mean (GA %)

Genetic advance ranged from 0.002 to 11.92 while the genetic advance in percent over mean ranged from 0.01 to 52.40 (Table 3). Number of nodes showed highest genetic advance 11.90. Single fruit weight and fruit diameter showed very low genetic advance. Highest genetic advance as a percent over mean was observed for number of nodes (52.40). While, moderate genetic advance as a percent over mean were observed for leaf number (17.48%). Moreover, the lower genetic advance as a percent over mean were observed in days to first flowering (2.29%), fruit number per plant (6.84%) and fruit length (2.02%). Furthermore, the lowest genetic advance as a percent over mean were observed in days to first fruiting, plant height, fruit diameter, single fruit weight and fruit yield per plant. Particularly, traits such as fruit length and fruit yield per plant exhibited low genetic advance despite moderate to high heritability, indicating a limited scope for improvement through direct phenotypic selection. This pattern suggests a predominant influence of non-additive gene effects and environmental factors, comparable observations were also noted by Temam (2020). This implies that heterosis breeding or selection in subsequent generations, as opposed to only phenotypic selection, may be a more effective way to improve these features. Low heritability coupled with low genetic advance for fruit diameter and single fruit weight suggests that these traits are predominantly governed by environmental effects and non-additive gene action, implying a weak response to direct selection. From a breeding perspective, improvement of these characters may therefore require alternative strategies, such as progeny testing, hybridization, or selection under controlled environments, rather than simple phenotypic selection, which agree with those reported earlier (Duggi *et al.*, 2013; Sharma & Prasad, 2010).

Principal Component Analysis (PCA)

Principal component analysis (PCA) revealed substantial genetic variability among the okra genotypes. The scree plot (Fig 1) showed a sharp decline in eigenvalues after the third principal component, confirming that the first three components accounted for the majority of the total variation. Accordingly, the first three principal components together explained 81.9% of the total variability indicating that these components effectively summarized the multidimensional trait variation. In terms of the total significant proportion of variance, which ranged from 41.4% to 7.6%, PC1 had the largest variance (41.4%), followed by PC2 (22.7%), PC3 (17.8%), and PC4 (7.6%) (Table 4). The first two principal components were therefore used for graphical interpretation.

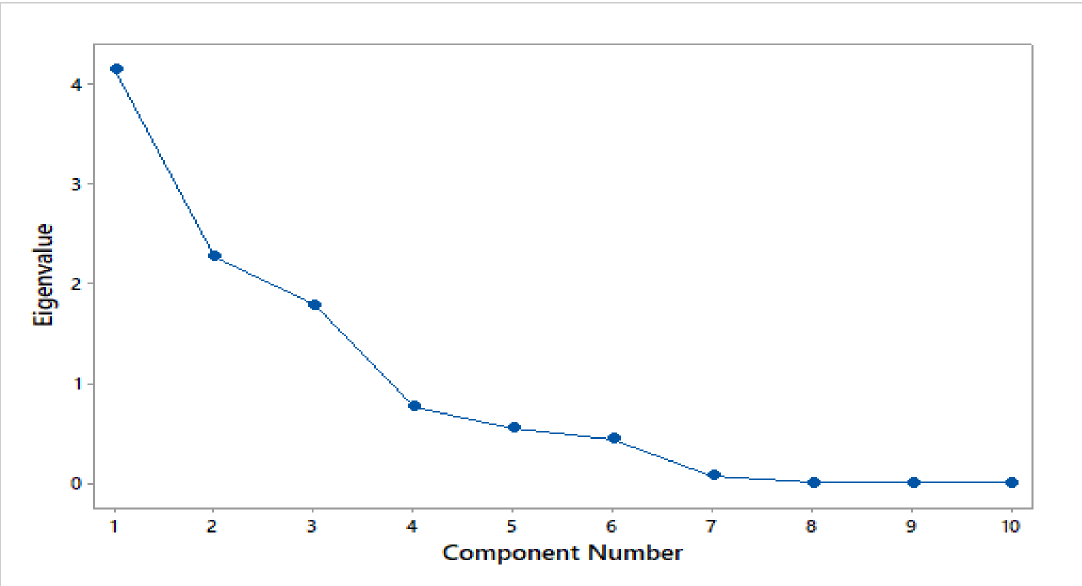

Figure 1. Scree plot illustrating eigenvalues of principal components derived from principal component analysis (PCA). The sharp decline after the third component confirms that PC1–PC3 explain the majority of the total variability among okra genotypes.

Table 4. Eigenvalues, proportion of variance and cumulative variance explained by principal components for yield and yield-related traits in okra

Principal Component	Eigenvalue	Proportion of Variance (%)	Cumulative Variance (%)
PC1	4.1438	41.4	41.4
PC2	2.2680	22.7	64.1
PC3	1.7824	17.8	81.9
PC4	0.7587	7.6	89.5
PC5	0.5442	5.4	95.0
PC6	0.4354	4.4	99.3
PC7	0.0676	0.7	100

PC = Principal Component

The first principal component (PC1) accounted for 41.4% of the total variation and was predominantly associated with yield and fruit-related traits (Fig 2). High positive loadings were observed for single fruit weight (0.424), fruit yield per plant (0.388), fruit length (0.362), days to first flowering (0.368), and fruit diameter (0.297), with fruit number per plant also contributrd positively (Table 5). These results indicate that PC1 primarily represented overall yield potential and fruit size attributes. Genotypes positioned along the positive direction of PC1 were characterized by superior yield performance, whereas those positioned negatively exhibited comparatively lower productivity. The second principal component (PC2) explained 22.7% of the total variation and was mainly influenced by plant height (0.387) (Fig 2). In contrast, number of nodes (−0.600), fruit yield per plant (−0.358), and fruit number per plant (−0.336) loaded negatively on this component. PC2 therefore reflected variation in plant architecture and phenological development, separating genotypes with vigorous vegetative growth from those with relatively compact growth habits and greater reproductive efficiency. The third principal component (PC3) contributed 17.8% of the total variation and was dominated by leaf number (−0.615), fruit length (−0.428), and fruit number per plant (0.430), highlighting the importance of foliage development and reproductive balance in explaining the remaining variability among genotypes. Although the magnitude varied, the overall trend agrees with the earlier studies (Shushay *et al.*, 2014; Bukola *et al.*, 2025)

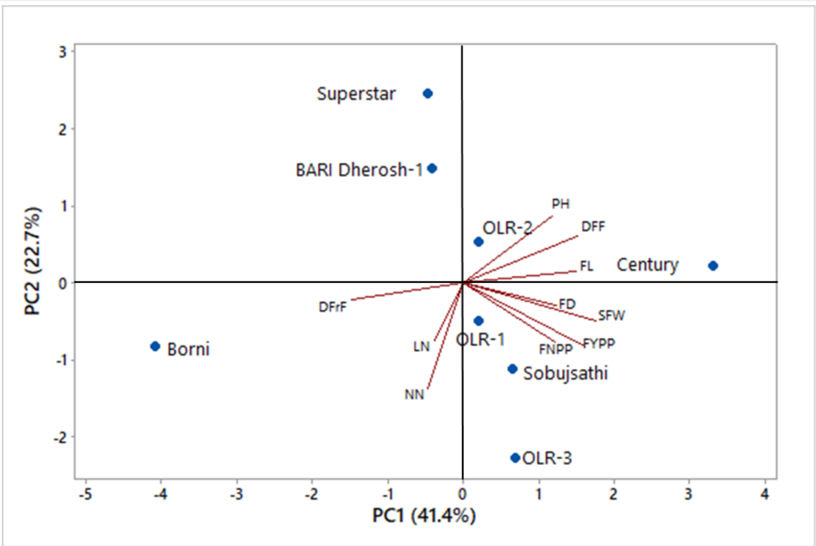

Figure 2. Principal component analysis (PCA) biplot showing the relationship among okra genotypes and yield-related traits.

Table 5. Factor loadings (eigenvectors) of major traits for the first four principal components

Trait	**PC1**	**PC2**	**PC3**	**PC4**
DFF	0.368	0.267	-0.035	0.182
DFrF	-0.359	-0.093	-0.254	0.447
PH	0.283	0.387	0.070	0.428
LN	-0.093	-0.323	-0.615	-0.106
NN	-0.113	-0.600	0.142	0.297
FNPP	0.292	-0.336	0.430	0.055
FL	0.362	0.068	-0.428	-0.202
FD	0.297	-0.122	-0.271	0.617
SFW	0.424	-0.213	-0.238	-0.230
FYPP	0.388	-0.358	0.182	-0.083

DFF = days to first flowering; DFrF = days to first fruiting; PH = plant height; LN = leaf number; NN = number of nodes; FNPP = fruit number per plant; FL = fruit length; FD = fruit diameter; SFW = single fruit weight; FYPP = fruit yield per plant

The PC1–PC2 biplot and score plot (Fig 2) revealed clear associations among traits, where acute angles between vectors indicated strong positive correlations, particularly among yield-contributing traits such as fruit yield per plant, single fruit weight, fruit number per plant, and fruit length. In contrast, an obtuse or near-orthogonal orientation was found between vegetative traits (leaf number and number of nodes) and yield-related traits. The genotype score in the plot demonstrated distinct grouping patterns among the okra genotypes. Century and OLR-3 were positioned in the positive region of PC1. Sobujsathi and OLR-1 occupied intermediate positions, reflecting balanced vegetative growth and yield performance. In contrast, Borni was located in the negative region of PC1. Superstar and BARI Dherosh-1 were mainly separated along PC2.

The positive correlation among yield-related traits in okra observed in the PCA biplot indicates that simultaneous improvement of these traits is effective. The pointed angles among vectors for fruit yield per plant, single fruit weight, fruit number per plant, and fruit length further suggest strong positive correlations, suggesting their importance as key selection criteria. On the other hand, the negative or orthogonal relationships between vegetative traits (leaf number and number of nodes) and yield traits suggest that excessive vegetative growth may not favor higher productivity. The PCA score plot effectively differentiated genotypes based on combined trait performance. Genotypes such as OLR-3 and Century, positioned in the positive region of PC1, exhibits superior yield potential and favorable fruit attributes, suggesting that they are suitable as parent material in breeding programs and also suitable for direct cultivation. Sobujsathi and OLR-1 exhibited intermediate positioning, reflecting balanced performance, while Borni consistently occupied the negative region, confirming its lower yield potential. The current findings agreed with the findings of (Ouedraogo *et al.,* 2024; Saleem *et al.*, 2023; Yousef *et al.,* 2018; Okatan, 2020).

Overall, the combined evaluation of genetic variability parameters and multivariate analyses clearly indicates that fruit yield per plant is primarily governed by its key component traits, notably fruit number per plant, fruit length, and single fruit weight. These traits cooperatively represent both productivity and sink strength, emphasizing their major role in yield determination under the studied environment. The observed variability pattern suggests that improvement of fruit yield per plant can be achieved more effectively through indirect selection targeting these major yield components rather than direct selection for yield alone. Emphasizing these attributes allows breeders to better capture additive genetic effects while reducing the influence of environmental variation, thereby enhancing selection accuracy and breeding efficiency.

Furthermore, the integration of component-trait selection with multivariate approaches, particularly PCA-based genotype grouping, provides an additional advantage by facilitating the identification of genotypes that combine superior yield potential with stable expression of critical traits. Such a strategy is expected to accelerate genetic gain and strengthen the effectiveness of okra improvement programs.

CONCLUSION

The present study clearly demonstrated the existence of substantial genetic variability among the okra genotypes under the agro-ecological conditions of AEZ-14, Bangladesh. Significant differences in phenological, vegetative, and yield-related traits indicate scope for genetic improvement through selection and breeding. Among the studied varieties, OLR-3, Century, and Sobujsathi exhibited superior fruit yield per plant, mainly due to favorable combinations of fruit number, fruit size, and single fruit weight, highlighting the importance of cumulative yield-contributing traits rather than early flowering alone.

The genetic variability analysis revealed that phenotypic coefficient of variation was higher than genotypic coefficient of variation for all traits, indicating environmental influence on trait expression. However, relatively narrow differences between PCV and GCV for fruit yield per plant, fruit length, fruit number per plant and number of nodes suggest a strong genetic control over these characters, making them reliable targets for selection. High heritability coupled with high genetic advance for number of nodes indicates the predominance of additive gene action and the effectiveness of direct selection for this trait. In contrast, moderate heritability with low genetic advance for fruit yield and fruit size traits suggests the involvement of non-additive gene effects, implying that advanced breeding approaches may be more effective for their improvement.

Principal component analysis further confirmed that yield and fruit-related traits were the major contributors to total genetic variation, with the first three components explaining most of the variability. Overall, the study emphasizes that fruit yield per plant, fruit number per plant, fruit length, and single fruit weight are key selection criteria for okra improvement, and genotypes with such favorable traits hold strong potential for cultivation and future breeding programs.

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