



ASSESSMENT OF GENETIC VARIATION AND TRAITS ASSOCIATION IN GARLIC (*ALLIUM SATIVUM* L.)

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SUMMARY

An evaluation of the genetic diversity and phenotypic variation among 17 garlic (*Allium sativum* L.) accessions occurred on 13 morphological traits using an augmented experimental design. Statistical analyses, including descriptive statistics, correlation analysis, cluster analysis, and principal component analysis (PCA), continued to assess the extent of variability and elucidate interrelationships among the traits. Key findings revealed significant variability in traits like plant height (44.8–77.7 cm), bulb thickness (36.96–69.52 mm), and bulb weight (18.75–96.05 g), indicating scope for these traits' improvement. Correlation analysis highlighted positive associations among traits, such as bulb thickness, stem thickness, and bulb weight, emphasizing their collective impact on yield. A trade-off between clove number and clove size was also noteworthy. Cluster analysis grouped accessions into two main clusters, aiding targeted breeding strategies. Distinct garlic accession 41083, identified as *Allium ampeloprasum*, displayed unique traits like pest and disease resistance. PCA confirmed substantial diversity, with 68% of the variance explained by the first two components. Accessions, including 36559 and 41433, emerged as promising candidates for introducing novel traits. These findings highlight the potential of morphological diversity in garlic breeding to enhance yield, adaptability, and market appeal for sustainable cultivation.

Keywords: Garlic (*A. sativum* L.), accessions, genetic diversity, morphological and yield traits, traits relationship, pest and disease resistance

Key findings: The latest study presents the genetic diversity analysis based on morphological traits, revealing high variability among garlic (*A. sativum* L.) accessions.

Communicating Editor: Prof. Naqib Ullah Khan

Manuscript received: September 13, 2024; Accepted: November 14, 2024.

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Citation: Rasheed S, Mahroof S, Gul S, Khan SU, Arshad M, Jatoy SA (2025). Assessment of genetic variation and traits association in garlic (*Allium sativum* L.). *SABRAO J. Breed. Genet.* 57(5): 1851-1861. <http://doi.org/10.54910/sabrao2025.57.5.7>.

INTRODUCTION

Garlic (*Allium sativum* L.) is a horticultural crop from the Alliaceae family, originally native to Central Asia. It now has a worldwide cultivation, with major production in countries such as Korea, China, India, the USA, Spain, Argentina, and Egypt. China stands out as the leading producer (Atif *et al.*, 2020). Garlic is prominent for its healing attributes, including boosting the immune system and reducing the risks of cancer, strokes, heart disease, and viral infections. It contains around 200 compounds with potential disease-preventive properties (Gebreyohannes and Gebreyohannes, 2013).

Garlic (*Allium sativum* L.) plants develop underground bulbs composed of small, clove-like bulbils encased in a thin, pink, or white skin. Garlic thrives in various climatic conditions, though it requires a moist, cool climate for optimal vegetative growth and a warm, dry environment for bulb maturation. It does not tolerate icy cold or heat (Khade *et al.*, 2024). Garlic's narrow, long leaves are also edible, and the plant is adaptable to both temperate and tropical regions. Its propagation is vegetative through bulbs, and it is ready for harvest when the tops turn brown or yellow.

Their morphological diversity includes variations in bulb and leaf size, shape, and color, as well as differences in flower color, height, and bulbil development within the inflorescence (Wang *et al.*, 2014). The reliance on underground cloves for reproduction limits the applicability of conventional breeding techniques used for sexually propagated crops. Garlic faces several challenges, namely, bolting, sterility, biotic and abiotic stresses, limited genetic variability, and temperature fluctuations, all of which impact producers and breeders (Suleria *et al.*, 2015).

Garlic exhibits broad variations under different ecological conditions and adaptability to specific environments through both artificial and natural selection. The development of new cultivars primarily employs clonal selection, induced mutation, and somaclonal variation (Chen *et al.*, 2014). However, due to the lack

of sexual reproduction, variability in garlic is limited, which affects the development of economically important traits, like earliness, yield, quality, and biotic and abiotic stress tolerance. Selecting suitable garlic varieties for diverse agro-climatic settings is crucial for meeting both export demands and domestic needs. Although garlic is propagating vegetatively, research on essential traits for an effective selection program remains scarce (Sandhu *et al.*, 2015).

This study sought to address these gaps by exploring the diversity of garlic accessions already collected by the national genebank from various parts of the country, as well as some entries mainly from China, Iran, and Italy, representing other countries. The research aimed to examine phenotypic variability and yield-related parameters, such as average bulb weight, single clove weight, the number of cloves per bulb, the weight of a single bulb, clove length, and clove width.

MATERIALS AND METHODS

The study commenced at the Plant Genetic Resource Institute, National Agricultural Research Centre (NARC), Islamabad, Pakistan, during 2020–2021. The plant material included 17 genotypes obtained from the National Genebank of Pakistan, NARC Islamabad. The passport information of the garlic germplasm studied is available in Table 1.

Sowing of garlic cloves started in mid-October, and harvesting occurred in the last week of April. The edaphic characteristics of the soil suggest a moderately fertile, slightly alkaline environment suitable for garlic cultivation (Table 2). Seed cloves planted on ridges had a row-to-row and a plant-to-plant distance of 30 and 10 cm, respectively. Following standard agronomic practices was successful during the growth period of garlic. Two rows with two-meter lengths, as prepared for each accession, comprised the recorded data for 10 plants. The garlic variety Desi Gulabi (41982) served as the check.

Table 1. Passport data of the garlic genotypes studied for phenotypic variability.

Accession #	Cultivar/Collection No.	Origin	Location
35738	7591-2	Pakistan	Skardu
36559	Iranian	Iran	--
36766	Italian	Italy	--
36767	Chinese	China	--
36768	AJK	Pakistan	--
36769	MJ-84	Unknown	--
38611	8209(6)	Pakistan	Shigar
41083	NARC HG-1	Pakistan	Islamabad
41433	China white	China	Swat
41434	China pink	China	Mansehra
41435	Swabi white	Pakistan	Swabi
41436	Swabi pink	Pakistan	Swabi
41437	Iranian white	Iran	Mansehra (local market)
41982	Desi Gulabi (Check)	Pakistan	Khairpur
41983	Garlic-1	Pakistan	--
41984	Garlic-2	Pakistan	--
41985	Garlic-3	Pakistan	--

Table 2. Physico-chemical analysis of the experimental soil at the NARC, Islamabad, Pakistan.

No.	Nitrate Nitrogen	Phosphorus (mg/kg)	Potassium	pH (1:1 Ratio)	EC (μ S/cm)	O.M. (%)	Texture Class
0-15	3.85	4.95	120	8.01	246	0.97	Clay Loam
0-30	1.98	1.05	91	7.92	268	0.70	

Data recorded

Data recorded for 13 morphological traits continued at different growth stages of the crop. Plant height (cm) measurement started from the top of the bulb to the tip of the longest leaf at maturity. Bulb thickness (mm) recording consisted of the widest point of the bulb after harvesting, while measuring stem thickness (mm) succeeded on mature, harvested plants at the maturity stage. Leaf sheath height (cm) determination began from the point of leaf emergence to its extreme tip. The number of leaves included counting fully matured garlic plants. The leaf length (cm) measured began from the base to the tip of a single leaf, with the leaf width (cm) recorded at the widest point of three randomly selected leaves. The extent of root length (cm) came from the base of the bulb to the tip of the longest root. The number of cloves per bulb also succeeded in counting. Recording the bulb weight (g) and individual clove weight (g) used a digital weighing balance. Clove length (mm)

had its measurement starting from the base to the tip of a single clove, while the recorded clove width (mm) comprised its widest point.

Data analysis

For the statistical analyses, methodologies employed included descriptive statistics, correlation analysis, and multivariate statistical analyses, particularly principal component analysis (PCA) and cluster analysis. Obtaining a clear understanding of the dataset's basic characteristics and acquiring insight into the central tendency, dispersion, and distribution of the data, calculation of descriptive statistics engaged STATISTICA (StatSoft, 2004).

Principal component analysis utilized R software, an open-source statistical computing environment. The study explored the relationships between variables and assessed the quantitative measure of the strength and direction of associations between variables, aiding in identifying highly correlated or independent variables, using a correlation

matrix computed in R software. Cluster analysis performed ran the NTSys2.1 (Rohlf, 2000) to group the data based on similarity, revealing patterns, underlying structures, and relationships, aiding in classification, predictive modeling, and understanding natural groupings within the dataset.

RESULTS AND DISCUSSION

Genetic variability among garlic accessions

The results provided insights into the variability and range of different morphological traits in garlic varieties. Most yield-contributing traits revealed moderate to high variability in the set of garlic accessions investigated (Table 3). The average plant height of garlic was 63.62 cm, with a considerable range from 44.8 cm (41083) to 77.7 cm (41433). The moderate variance (78.65) for this trait indicated noticeable variability among accessions. Garlic accession 41433 has the tallest plants, while 41083 showed the shortest height, reflecting genetic diversity and possible environmental adaptability in different varieties. The bulb thickness displayed a high variation, ranging from 36.96 mm (41982) to 69.52 mm (41083), with a mean value of 53.20 mm. Bulb thickness plays a critical role in the yield potential and market value of garlic, and the

moderate variance (47.72) suggests that while there is some variability among varieties, most fall within a predictable range. Garlic accession 41083 has the thickest bulbs, while 41982 is the smallest, implying different growing conditions or genetic factors. For biodiversity, genetic variability is crucial in a population because it becomes difficult for a population to adapt to environmental changes and hence makes it more prone to extinction without variability. Pervin *et al.* (2014) found high variability among 25 garlics for leaf length, plant height, bulb yield, and number of cloves per bulb in very high genotypes.

Leaf length influences the plant's ability to capture light and perform photosynthesis. The high variance (80.47) indicates significant variability in garlic. On average, a garlic bulb contains 14.84 cloves, with a minimum number of 6.1 (41083) to 32.3 (41433). The high variance (38.08) signified some varieties produce many more cloves than others, which could be due to genetic factors. The number of cloves has a direct relation to the yield and marketability of garlic. The mean bulb weight is 37.63 g, with a large range from 18.75 g (41982) to 96.05 g (41083), indicating that heavier bulbs are the typical preference in the market for their higher yield. The highest variance (301.84) indicates the greatest variability among traits, suggesting that bulb weight incurred high influences from both genetic diversity and environmental factors.

Table 3. Variability pattern in garlic genotypes based on phenotypic traits.

Traits	Mean $\pm$ SE	Variance	Range
Plant height (cm)	63.62 $\pm$ 2.15	78.65	44.8 (41083)–77.7 (41433)
Bulb thickness (mm)	53.20 $\pm$ 1.68	47.72	36.96 (41982)–69.52 (41083)
Stem thickness (mm)	14.11 $\pm$ 0.87	12.87	7.4 (41982)–17.57 (41984)
Leaf sheath height (cm)	16.14 $\pm$ 0.54	4.99	12.15 (36768)–19.57 (41433)
Leaf number	8.93 $\pm$ 0.46	3.6	5.3 (41083)–11.1 (41984)
Leaf length (cm)	42.74 $\pm$ 2.18	80.47	28.15 (36559)–54.2 (35738)
Leaf width (cm)	1.86 $\pm$ 0.07	0.09	1.2 (41436)–2.2 (41434)
Root length (cm)	8.62 $\pm$ 0.48	3.97	5.37 (36766)–11.96 (41083)
Cloves number	14.84 $\pm$ 1.50	38.08	6.1 (41083)–32.3 (41433)
Bulb weight (g)	37.63 $\pm$ 4.21	301.84	18.754 (41982)–96.05 (41083)
Clove weight (g)	3.04 $\pm$ 0.65	7.25	1.15 (36767)–13.04 (41083)
Clove length (mm)	23.67 $\pm$ 0.87	12.8	19.85 (41436)–35.78 (41083)
Clove width (mm)	13.48 $\pm$ 0.58	5.7	9.41 (41436)–18.23 (41083)

The minimum stem thickness resulted in 41982 (7.4 mm), and the maximum of 17.57 mm was in 41984, with an average stem thickness of 14.11 mm. The thicker stems can be an indicator of plant robustness and better nutrient transport. A low variance was also evident in different morphological traits, viz., leaf sheath height (4.99), the number of leaves (3.60), leaf width (0.09), and clove width (5.70). The low variability in these traits implies their greater conservation and stability across varieties, which may not vary significantly across different environments or varieties. After the estimation of 24 garlic accessions assembled from the main cultivation of Iran, Awel *et al.* (2011) stated that bulb-to-bulb variations gained effects from their breeding status. Assessments on the genetic variability, heritability, and genetic advance in 48 different exotic and local collections of ginger guided that a bigger portion of phenotypic variability was genetic and exceptionally heritable in many of the cases. Yield-contributing traits, such as clove weight (0.83), the number of cloves (0.83), and yield per plot (0.84), demonstrated significant diversity among garlic accessions. Additionally, quantitative traits, i.e., leaf length, leaf width, shaft thickness, and shaft length, exhibited high intergenetic variation, as reported by Shrestha *et al.* (2022). This diversity in both agronomic and morphological traits is critical for garlic breeding programs.

Quantitative traits are particularly valuable in breeding efforts due to their direct relationship with yield and other agronomic characteristics (Panthee *et al.*, 2006). The observed moderate to high variation in traits, such as plant height, clove size, bulb weight, and bulb diameter, provides breeders with opportunities to select and develop high-yielding, robust varieties (Singh and Dobey, 2015). Significant diversity was also notable in agronomic traits like drought tolerance, stress response, bulb size, and growth habit (Panthee *et al.*, 2006). Traits—stem thickness and leaf sheath height—displayed relatively low variability, suggesting genetic stability, while highly variable traits, like bulb weight, clove number, and leaf length, offer substantial

potential for targeted breeding efforts. These findings underscore the utility of exploiting existing variability to enhance garlic yield, adaptability, and market desirability (Singh *et al.*, 2012).

Clustering pattern of garlic accessions

The cluster analysis of garlic germplasm identified two major clusters along with two distinct operational taxonomic units, or OTUs (Figure 1). The clustering pattern provided critical insights into the genetic relationships among garlic varieties and their potential utility in breeding programs. Cluster A emerged as the larger group, encompassing a wide range of accessions, including 36766, 41983, 41984, 41985, 38611, 41434, 36767, 41435, 36769, 36768, and 35738. These genotypes shared genetic similarities, suggesting a common ancestry or similar selective breeding histories. These results are in line with the findings of Jaynes *et al.* (2003), who reported cluster analysis confiscates genotypes into clusters, which shows vast similarity within a cluster and dissimilarity between clusters.

Further subdivision within Cluster A revealed two subgroups: subgroup 1, including 36767, 41434, 41984, and 41985. These varieties implied close genetic relations, likely due to shared origins or selection for similar traits, such as bulb size, color, or environmental adaptability. Subgroup 2 contained 36766, 41983, 38611, 41435, 36769, 36768, and 35738. Within this subgroup, 41435 and 36769 showed particularly close genetic ties, possibly due to selection under comparable environmental conditions or local adaptation. Conversely, the 36766 displayed distinctiveness, reflecting its unique breeding or evolutionary path, potentially influenced by different cultivation practices or ecological factors. Cluster B, although smaller, demonstrated considerable genetic variation, consisting of 41433, 41982, 41436, and 36559. Among these, 36559 and 41436 appeared more closely related, possibly due to geographical proximity or shared environmental adaptations. The 41433 stood out as genetically distinct, probably possessing

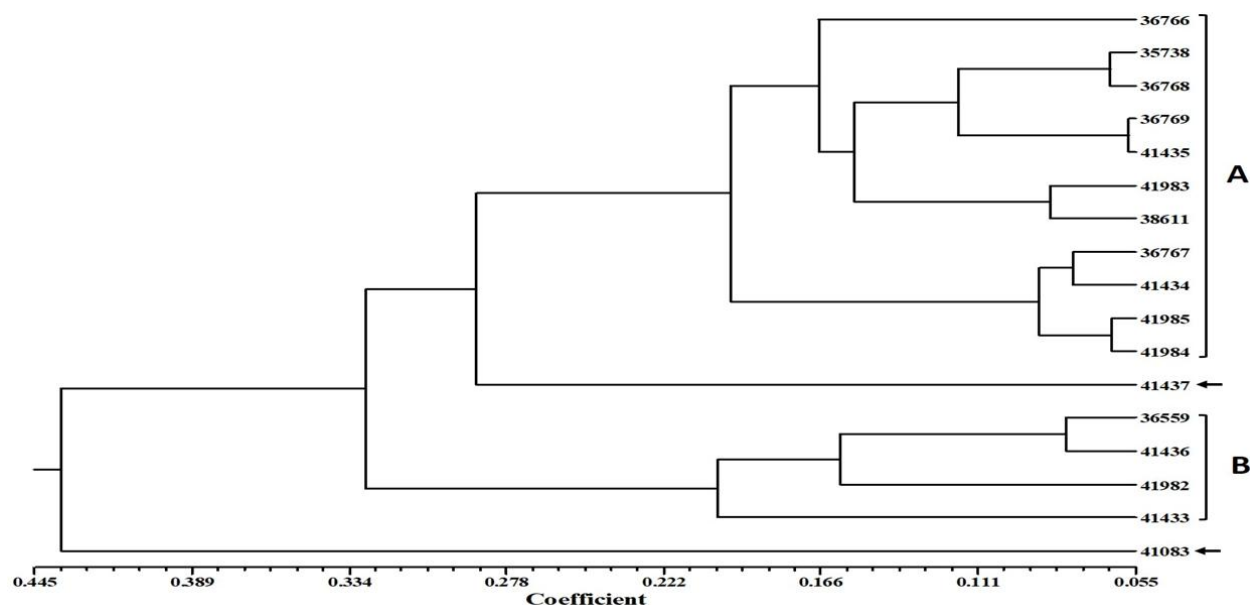


Figure 1. Genetic relationship among the garlic accessions based on the clustering pattern.

unique traits, such as disease resistance, climate adaptability, or specific bulb characteristics.

The accession 41437 formed a distinct OTU; while it shares some genetic similarities with Cluster A, it maintains enough unique characteristics to be classified separately. These unique traits could include resistance to environmental stresses or specialized morphological features, making it a valuable resource for breeding programs. Accession 41083 represents the second OTU, genetically isolated from Clusters A and B. The 41083 creates its own cluster, identified as belonging to a different species, *Allium ampeloprasum*, underscoring its potential as a reservoir for entirely novel traits, such as pest tolerance, disease resistance, or other valuable agricultural features.

This grouping pattern of garlic genotypes indicated no correlation between geographical distribution of genotypes and genetic divergence. Previous findings support the presented results (Ebrahimi *et al.*, 2019), stating no association among geographical region and genotypes clustering might be due to the exchange of material freely between different locations. Another study also confirmed the absence of a relationship

between diversity and geographical origins, as existing genotypes with similar origins come clustering into multiple groups (Tesfaye, 2022).

Notably, 41083 form distinct OTUs. Accession 41437, with its genetic uniqueness, can introduce novel traits into conventional garlic (*Allium sativum*), while 41083, as *Allium ampeloprasum*, offers unique traits absent in *A. sativum*. This diversity provides a foundation for cross-breeding to enhance traits like yield, disease resistance, and adaptability, ensuring productivity and sustainability in garlic cultivation. The formation of more clusters with a variable number of entries in each cluster is indicative of diversity, and accessions belonging to the cluster with maximum inter-cluster distance are genetically more divergent (Tesfaye, 2021).

Inter-cluster variation

Inter-cluster variation among garlic accessions revealed key differences in morphological traits (Table 4). Accessions in Cluster A exhibited higher mean values for most traits, except for the number of cloves and leaf sheath height, indicating their superior performance in yield-

Table 4. Inter-cluster variation in garlic genotypes based on quantitative traits.

Trait	Code	Cluster-1	Cluster-2
Plant height (cm)	PH	65.985 ± 8.09	59.27 ± 9.26
Bulb thickness (mm)	BT	54.97 ± 2.07	47.28 ± 6.47
Stem thickness (mm)	ST	16.432 ± 1.05	9.84 ± 2.28
Leaf sheath height (cm)	LSH	15.64 ± 2.41	17.05 ± 1.65
Leaf number	LN	9.88 ± 1.57	7.18 ± 0.94
Leaf length (cm)	LL	47.18 ± 6.67	34.59 ± 6.73
Leaf width (cm)	LW	2.02 ± 0.16	1.55 ± 0.24
Root length (cm)	RL	9.76 ± 1.40	6.52 ± 0.78
Cloves number	CN	11.63 ± 2.49	20.70 ± 6.75
Bulb weight (g)	BW	37.19 ± 6.63	28.28 ± 9.53
Clove weight (g)	C.wt	2.72 ± 0.71	1.87 ± 0.62
Clove length (mm)	CL	24.67 ± 3.88	21.82 ± 2.11
Clove width (mm)	CW	14.75 ± 1.40	11.14 ± 2.03

contributing parameters, such as bulb size, clove weight, and overall plant size. These traits suggest shared genetic factors that make Cluster A accessions particularly suitable for high-yield garlic production and market value enhancement (Yadav *et al.*, 2018).

In contrast, Cluster B included accessions with lower mean values across most traits, which could indicate lower productivity or adaptation to different environmental conditions. For instance, accession 41982, though not high-yielding, is valued for its strong pungency, catering to specific consumer preferences. This analysis underscores the breeding potential of Cluster A accessions for enhancing yield, while Cluster B offers traits like environmental resilience or niche market appeal. These findings provide a strategic framework for optimizing garlic productivity and adaptability across diverse cultivation environments. Therefore, the study suggests that accessions with large cluster distances are the ultimate selection to enhance genetic variability for bulb yield improvement (Singh *et al.*, 2013). Similar findings came from Khar *et al.* (2008). Lower inter-cluster values provided the genotypes within these clusters were not significantly diverse from each other, whereas higher inter-cluster distance signaled greater divergence between the genotypes of these clusters (Yadav *et al.*, 2018).

Traits relationship

The correlation analysis of garlic traits revealed intricate relationships among growth parameters, demonstrating their collective influence on yield and quality (Figure 2). Plant height showed a positive and significant correlation with the number of leaves and leaf length, indicating that taller plants generally have more and longer leaves. These traits play a critical role in photosynthesis, contributing directly to plant growth and productivity (Habuš *et al.*, 2023).

The number of leaves also exhibited a positive relationship with key yield components, including the number of cloves, leaf width, bulb thickness, and stem thickness. This suggests that plants with more leaves can better support bulb development and overall growth. Bulb thickness, a pivotal yield determinant, appeared positively associated with root length and the number of leaves, emphasizing its influence on bulb size and yield potential. Interestingly, bulb thickness had no significant correlation with plant height or clove length, implying the involvement of other factors in these traits. Similar results have emerged from other researchers (Tesfaye *et al.*, 2021).

Bulb weight, another critical yield parameter, manifested a positive correlation

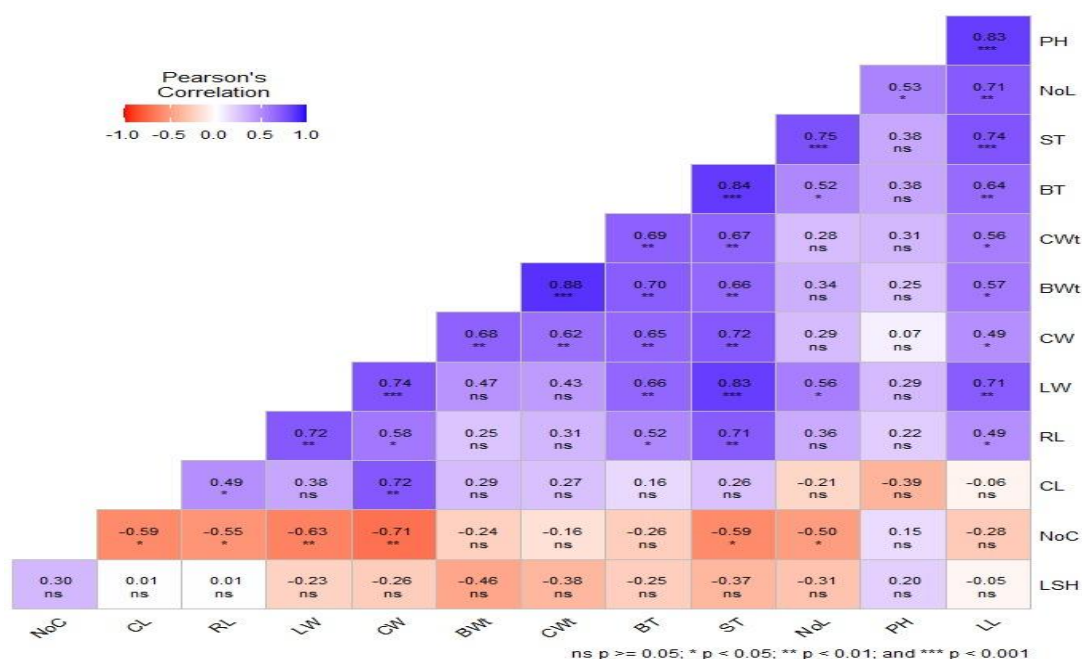


Figure 2. Pearson's correlation between quantitative traits of garlic genotypes. (PH = Plant height, BT = Bulb thickness, LSH = Leaf sheath height, NoL = Number of leaves, LL = Leaf length, LW = Leaf width, RL = Root length, NoC = Number of cloves, BWt = Bulb weight, CW = Clove weight, CL = Clove length, and CWT = Clove width).

with traits like leaf length, stem thickness, bulb thickness, and clove width, suggesting that robust plants with thicker stems and bulbs yield heavier, more marketable garlic. Leaf width also showed a positive correlation with leaf length, bulb and stem thickness, and clove width, but had a negative relationship with the number of cloves, indicating that broader leaves could enhance bulb characteristics while reducing clove numbers.

Similar findings also resulted from the study by Awale *et al.* (2011), stating bulb yield sustained impacts from most of the quantitative traits like stem thickness, bulb thickness, leaf length, and bulb diameter. This outcome is in contradiction with Kassahun (2006), who reported that quantitative characters have a positive direct effect on yield-related traits, but in onions, these parameters exhibit a negative effect on bulb yield. The number of cloves had a negative correlation with clove length, root length, and stem thickness. This pointed to a trade-off; garlic varieties with more cloves typically have

smaller cloves, thinner stems, and shorter roots. Traits, such as bulb thickness, stem thickness, and clove weight, emerged as positively correlated with essential yield parameters like bulb weight and clove width, highlighting their importance in high-quality garlic production. Hosamani *et al.* (2010) also disclosed that the number of cloves per bulb, bulb diameter, plant height, and clove length showed negative effects on bulb yield. Conversely, leaf width, the number of leaves per plant, bulb weight, and bulb length exhibited positive influences on yield. For optimum yield and market value, garlic breeders should prioritize traits such as bulb thickness, stem thickness, and leaf characteristics. Genotypes with moderate clove numbers but larger bulbs and cloves could be more desirable for commercial cultivation (Raju *et al.*, 2013).

Leaf width and root length, which positively impact yield-related traits, could entail further improvement through targeted management practices like optimized irrigation

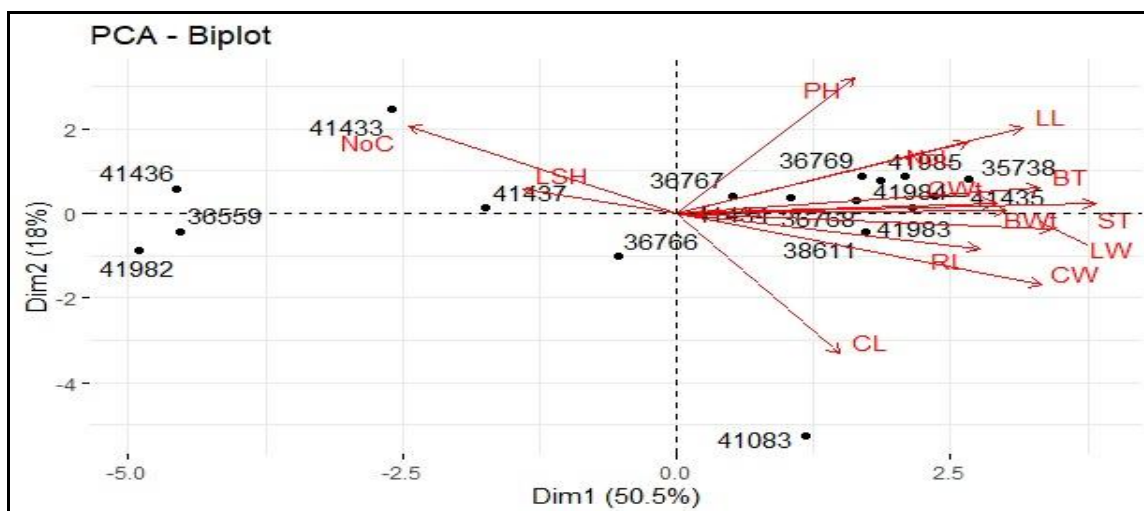


Figure 3. Principal component analysis showing the distribution pattern of 17 garlic accessions and studied parameters. (PH = Plant height, BT = Bulb thickness, LSH = Leaf sheath height, NoL = Number of leaves, LL = Leaf length, LW = Leaf width, RL = Root length, NoC = Number of cloves, BW = Bulb weight, CW = Clove weight, CL = Clove length, and CW = Clove width).

and nutrient application (Atinafu, 2022). The significant positive correlations between bulb weight and traits, like leaf length and stem thickness, suggest that agronomic practices enhancing plant vigor can further boost garlic yield. Similarly, to improve bulb yield in garlic leaf weight, considering bulb weight and clove length should be a must in the selection (Desta *et al.*, 2021; Usman *et al.*, 2015).

Principal component analysis

The principal component analysis (PCA) of garlic accessions revealed substantial genetic diversity, as shown in their distribution across the PCA scatterplot (Figure 3). The first two principal components (PCs) accounted for 68% of the total variance (Table 5), highlighting the bifurcation in primary and secondary patterns of variation in the dataset.

Accessions, such as 36766, 36559, 41982, 41433, 41436, and 41437, reached wide dispersions on the biplot, indicating unique genetic characteristics. In contrast, genotypes 36767, 35738, 41985, 41983, 38611, 41434, 36769, 36768, 41435, and 41984 formed clusters, reflecting lower genetic variability and similar morphological traits.

Notably, 41083 was highly distinct, particularly due to its superior clove length and width, making it a promising candidate for improving bulb and clove traits. This clustering and dispersion provide insights for breeding programs, such as combining distinct genotypes to introduce variability or selecting clustered genotypes to enhance uniformity (Kaushik *et al.*, 2016).

The traits contributing to diversity included plant height, leaf length, leaf width, clove length, clove width, the number of cloves, bulb thickness, bulb weight, and stem thickness. The observed patterns align with findings in other crops. Sharma *et al.* (2018) identified highly dispersed genotypes as valuable parents for onion breeding, while Afuape *et al.* (2011) used PCA to select superior genotypes in potatoes and sweet potatoes, respectively. Similarly, garlic accessions, such as 36766, 36559, 41982, 41433, 41436, and 41437, hold potential for introducing novel traits and improving adaptability and productivity. Integrating PCA with molecular techniques could further enhance understanding of the genetic basis for phenotypic diversity, enabling more targeted breeding strategies (Tesfaye, 2022).

Table 5. Eigenvalue (%), variance, and cumulative (%) of quantitative traits of garlic genotypes.

PCs	PC1	PC2	PC3
Eigenvalue	6.56	2.34	1.5
Percent	50.51	18.01	11.6
Cumulative %	50.51	68.52	80.12
Eigen Vector			
Plant height (cm)	0.1591	-0.5285	0.1717
Bulb thickness (mm)	0.3259	-0.0994	-0.1346
Stem thickness (mm)	0.3752	-0.0380	0.0318
Leaf sheath height (cm)	-0.1375	-0.0939	0.4934
Leaf number	0.2613	-0.2756	0.1581
Leaf length (cm)	0.3108	-0.3339	0.1356
Leaf width (cm)	0.3375	0.0587	0.2235
Root length (cm)	0.2721	0.1361	0.3860
Cloves number	-0.2399	-0.3361	-0.2588
Bulb weight (g)	0.2960	-0.0118	-0.4546
Clove weight (g)	0.2864	-0.0413	-0.4293
Clove length (mm)	0.1466	0.5457	0.0825
Clove width (mm)	0.3269	0.2798	-0.0250

CONCLUSIONS

This study analyzed the genetic and morphological diversity of garlic accessions using advanced statistical methods. The findings highlighted the potential of genetic variability in developing high-yield, adaptable, market-preferred cultivars. Integrating molecular and morphological approaches could enhance breeding efforts, supporting sustainable garlic production and advancing precision agriculture. Accession 41083 has emerged as a unique cultivar with valuable traits, including higher allicin content, making it ideal for nutritional, industrial, and pharmaceutical uses. These attributes warrant further comprehensive research on this accession. Future research should emphasize genome-wide association studies and environmental adaptability assessments to enhance garlic breeding strategies and support the development of improved cultivars.

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