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Agro-morphological characterisation and antioxidant profiling of long-day garlic (*Allium sativum*) genotypes from India

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ABSTRACT

The present study was carried out during the year 2022–23 and 2023–24 at ICAR-Indian Agricultural Research Institute, Regional Station, Katrain, Himachal Pradesh on agro-morphological characterisation and antioxidant profiling of six long day garlic (*Allium sativum* L.) genotypes developed along with one check cultivar, viz. Agrifound Parvati. Significant variations were observed among the seven genotypes of garlic for different horticultural and quality traits. On the basis of mean performance, genotype 'KTGRL-1' recorded highest bulb yield (617.29 q/ha) followed by 'KTGRL-2' (566.63 q/ha). Besides this, 'KTGRL-1' also had appreciable amount of total phenolics (445.63 µg gallic acid/g FW), cupric reducing antioxidant capacity (CUPRAC) (3.70 µ mol trolox/g), ferric reducing antioxidant power (FRAP) (1.71 µ mol trolox/g) and ascorbic acid (5.86 mg/100 g). Further, estimates of heritability along with genetic gain were observed high for leaf width, average clove weight, average bulb weight, bulb yield/ha, total phenolics, CUPRAC, FRAP and ascorbic acid, which highlighted the importance of additive gene action for the control of these traits and are more reliable for effective selection in garlic improvement. Principal component analysis (PCA) identified six most relevant principal components which account for 95.00% of the variance across all attributes. Further, results pertaining to correlation and path analysis revealed that selection based on average bulb and clove weight, number of cloves per bulb, bulb polar and equatorial diameter, leaf length and width, and plant height would be a fruitful strategy for yield improvement in garlic.

Keywords: *Allium sativum* (L.), Correlations, Path analysis, Principal components, Quality, Variability

Garlic (*Allium sativum* L.), a member of the Amaryllidaceae family, is one of the most extensively grown bulbous crops next to onion. Garlic is grown in an area of 0.41 million ha with the production of 3.26 million tonnes and productivity of 7.95 t/ha in India whereas, onion (*Allium cepa* L.) is grown in 1.74 million ha area with the production of 30.20 million tonnes and productivity of 17.36 t/ha (FAOSTAT 2023). It has abundance of vitamins, proteins, fats, calcium, potassium, phosphorus, sulphur, iodine, and silicon (Dixit *et al.* 2021). The physiologically active phytomolecules found in garlic are flavonoids, phenolic acids, allyl thiosulfinates and organosulfur compounds. Garlic's health benefits are mostly attributed to its bioactive chemicals, particularly its phenolic compounds (Lanzotti 2006 and Corzo-Martinez *et al.* 2007), which are found in comparatively large concentrations and have intriguing pharmacological qualities (Beato *et al.* 2011). Simon (2001) states that the majority of the variation that has been recognized comes from the wild progenitor and has been sexually reproduced into present cultivars. Furthermore, given its lengthy cultivation history, it is possible that naturally occurring mutations brought about by various environments are accountable for the observed phenotypic variability (Panthee *et al.* 2006 and Hoogerheide *et al.* 2017). It is vital to choose a variety that is suited for growing under different agro-climatic conditions in order to meet both domestic and export demand. Since garlic grows vegetatively, clonal-selection, induction of mutations, creation of somaclonal variations and genetic engineering are the methods used to create variability and breed new cultivars.

The phenotypic coefficients of variation (PCV) and genotypic coefficients of variation (GCV), heritability, genetic gain, and other genetic characteristics must all be evaluated in order to discrete the observed variations into heritable and non-heritable components. To select the appropriate characteristics from a diverse population, it may be helpful to comprehend the connections between quantitative characters, notably the yield and the features that are linked to it (Singh *et al.* 2024). While selecting two opposed desirable characters that affect the major character,

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genotypic and phenotypic correlations show the degree of relationship with various characters and provide a foundation for the selection process. Path-coefficient analysis assesses the cause-effect relationship and efficient selection. It also makes it easier to assess the extent of correlation between yield and its attributing traits (Singh *et al.* 2023). Besides this, the degree to which yield and yield-related traits exhibit genetic diversity determines how successful selection performs (Tsega *et al.* 2010). A meagre work has been done on characterisation and evaluation for yield and quality traits in garlic, which are necessary before implementing a selection procedure (Sandhu *et al.* 2015). Therefore, in light of these considerations, a comprehensive study was carried out on agro-morphological characterisation and antioxidant profiling of long day garlic genotypes developed at ICAR-Indian Agricultural Research Institute, Regional Station, Katrain, Himachal Pradesh.

MATERIALS AND METHODS

Experimental material and layout: The experiment was conducted during 2022–23 and 2023–24 at ICAR-Indian Agricultural Research Institute, Regional Station (32°05'53"N, 77°08'09"E; at an elevation of 1462 m amsl), Katrain, Kullu, Himachal Pradesh to assess agro-morphological characters and antioxidant profiling of long day garlic genotypes. Seven genotypes of long-day garlic, viz. KTGRL-1, KTGRL-2, KTGRL-3, KTGRL-4, KTGRL-5, KTGRL-6 and Agrifound Parvati (standard check) were used in this study (Supplementary Table 1). The trial was laid out in randomised complete block design (RCBD) at a spacing of 10 cm within plants and 15 cm between rows, with three replications of each genotype. The standard package of practices were followed to raise the healthy crop.

Data collection: Observations were recorded for 13 morphological traits, viz. Plant height [PH] (cm), Number of leaves/plant [NLPP], Leaf length [LL] (cm), Leaf width [LW] (cm), Neck thickness [NT] (cm), Bulb polar diameter [BPD] (cm), Bulb equatorial diameter [BED] (cm), Number of cloves/bulb [NCPB], Clove length [CL] (cm), Clove width [CW] (cm), Average clove weight [ACW] (g), Average bulb weight [ABW] (g) and Bulb yield/ha [BYPH] (q/ha) by randomly selecting five competitive plants in each entry in the every replication during both the years at neck fall stage.

The concentrations of six biochemical traits, viz. Total soluble solids [TSS] (ºBrix), Dry matter [DM] (%), Total phenolics [TP] (µg gallic acid/g FW), Cupric reducing antioxidant capacity [CUPRAC-] (µ mol trolox/g), Ferric reducing antioxidant power [FRAP] (µ mol trolox/g) and Ascorbic acid [AA] (mg/100 g) were estimated in this study. The TSS (ºBrix) were estimated using Erma hand refractometer, while dry matter content was estimated by using the following formula:

$$\text{Dry matter content} = (\text{Dry weight}/\text{Fresh weight}) \times 100$$

Phenolic content was determined by using Folin-Ciocalteu's (Singleton and Rossi 1965) method. To estimate the CUPRAC, a procedure described by Apak *et al.* (2006), following some modifications, was used. The FRAP concentration was estimated as per the method described by Benzie and Strain (1996) after making some minor modifications. The ascorbic acid was estimated by the direct colorimetric method described by Ranganna (2008).

Data analysis: The pooled data of two years (2022–23 and 2023–24) were subjected to analysis of variance (ANNOVA) in OPSTAT software as per the procedure given by Gomez and Gomez (1984). The PCV, GCV and heritability (h^2) were examined statistically on pooled data in accordance with Burton and De Vane (1953). Genetic advance (GA) was calculated following Johnson *et al.* (1955). The methods of Al-Jibouri *et al.* (1958) and Dewey and Lu (1959) were implemented to assess the genotypic coefficients of correlation. The direct and indirect effects of component traits on bulb yield per hectare were calculated using correlation coefficients of various component traits as suggested by Wright (1921) and elaborated by Dewey and Lu (1959). The principal component analysis was carried out using past 4.14 software to identify the main traits that account for most of the variations among the genotypes under study.

RESULTS AND DISCUSSION

Mean performance: Significant variations were recorded among the seven genotypes of long-day garlic for different horticultural and biochemical traits studied (Table 1). The pooled data of two years (2022–23 and 2023–24) revealed that the genotypes exhibited significant variations for yield and other related traits under study, viz. PH (76.24–84.92 cm), NLPP (9.47–11.85), LL (44.92–61.04 cm), LW (2.37–3.35 cm), NT (1.09–1.46 cm), BPD (4.45–5.59 cm), BED (5.44–6.58 cm), NCPB (12.88–17.46), CL (2.99–3.46 cm), CW (1.88–2.42 cm), ACW (4.75–9.38 g), ABW (72.30–117.66 g) and BYPH (381.01–617.29 q). Besides this, substantial variations were also recorded for different quality traits, viz. TSS (27.90–36.07ºB), DM (27.49–35.70%), TP (339.63–457.69 µg gallic acid/g FW), CUPRAC (1.93–3.90 µ mol trolox/g), FRAP (0.48–1.71 µ mol trolox/g) and AA (2.67–6.05 mg/100 g). This revealed that genotypes have a significant degree of genetic variation which would offer a great deal of opportunity for genetic improvement of long-day garlic. Based on the mean performance of different genotypes, KTGRL-1 recorded highest bulb yield (617.29 q/ha) followed by KTGRL-2 (566.63 q/ha). Besides this, genotype KTGRL-1 also contained appreciable amount of TP (445.63 µg gallic acid/g FW), CUPRAC (3.70 µ mol trolox/g), FRAP (1.71 µ mol trolox/g) and AA (5.86 mg/100 g). On the other hand, highest TSS (36.07ºBrix) and DW (35.70%) was observed in the genotype, KTGRL-4, while 'KTGRL-2" also contained the considerable amounts of TSS (34.20ºBrix), DM (32.99%) and TP (443.36 µg gallic acid/g FW). Singh *et al.* (2012), Dixit *et al.* (2021a), Anand *et al.* (2022), Kaushal *et al.* (2025) and Pasazade and Hanci (2025) have also observed significant variations in their respective breeding materials of garlic.

Parameters of variability: The extent of variations present in the existing germplasm forms the basis for development of a breeding programme for the genetic improvement of any crop. In present studies, the PCV were found to have higher values than the corresponding GCV for all the traits under study (Table 2), though difference was very less in most of the cases. Thus, revealing that these traits are less affected by environmental factors. Tsega *et al.* (2010), Dixit *et al.* (2021a) and Tesfaye (2021) had also reported greater PCV estimates than GCV in their respective studies. The pooled data of 2022–23 and 2023–24 revealed that the estimates of PCV and GCV were recorded high (>20%) for FRAP (33.11% and 32.56%), AA (31.85% and 31.60%), CUPRAC (27.51% and 27.20%), ACW (25.53% and 23.40%), BYPH (20.99% and 18.24%) and ABW (20.94% and 18.48%), respectively. This reflects that these genotypes have greater genetic variability for these traits for making further improvement by selection. In the meanwhile, moderate (10–20%) estimates of PCV and GCV were observed for LW (13.71% and 12.06%), NCPB (12.24% and 10.10%), TP (11.07% and 10.41%), NT (10.90% and 10.14%), CW (10.87% and 9.76%), LL (10.24% and 9.64%) and TSS (10.06% and 8.84%), respectively. On the other hand, low estimates (<10%) were recorded for NLPP (9.42% and 8.59%), BPD (8.90% and 8.62%), DM (8.74% and 8.63%), BED (7.45% and 6.63%), CL (6.14% and 5.75%) and PH (3.83% and 3.42%), respectively. Earlier studies have also identified high or medium levels of PCV and GCV for yield/plant, bulb equatorial diameter, number of leaves and bulb weight (Tesfaye 2021), leaf length, weight of clove and yield/plant (Tsega *et al.* 2010), number of cloves/bulb and marketable yield (Dubey *et al.* 2010) in garlic.

Burton and De Vane (1953) had opinion that selection in combination with the GCV may be used to estimate the extent of improvement that would be predicted based on a measure of heritable variations called as heritability. The pooled data of two years showed that the heritability estimates were recorded high (>60%) for all the traits studied which specified the greater role of a genetic component of variation and less influence of the environment. High heritability estimates for a variety of yield-contributing variables had also been reported by Dubey *et al.* (2010), Sandhu *et al.* (2015) and Tesfaye (2021) for their respective breeding materials.

The high estimates (>20%) of genetic gain were observed for AA (64.56%), FRAP (60.93%), CUPRAC (55.38%), ACW (44.18%), ABW (33.62%), BYP (32.64%), LW (21.85%) and TP (20.16%), while genetic gain was observed moderate for rest of the traits except plant height (6.27%) having low genetic gain (<10%) over pooled data of two years. As Johannsen (1909) pointed out, high heritability does not always imply significant expected genetic development. Thus, predictions based on heritability and genetic advance may be more useful for determining the actual effects of selection (Sharma *et al.* 2016). In our studies, high heritability along with high genetic gain was observed for LW, ACW, ABW, BYPH, TP, CUPRAC, FRAP

Table 1 Mean performance of long day garlic genotypes for yield and quality traits (Pooled data of 2022–23 and 2023–24)

Genotypes / Traits	PH	NLPP	LL	LW	NT	BPD	BED	NCPB	CL	CW	ACW	ABW	BYPH	TSS	DM	TP	CUPRAC	FRAP	AA
KTGRL-1	84.92	9.65	61.04	2.98	1.29	5.35	6.42	15.19	3.46	2.37	8.41	117.66	617.29	30.58	29.56	445.63	3.70	1.71	5.86
KTGRL-2	81.36	9.47	53.41	3.35	1.35	4.45	6.58	17.46	3.03	2.42	9.38	107.27	566.63	34.32	32.99	443.36	2.01	1.40	3.72
KTGRL-3	78.18	11.85	53.31	2.41	1.46	5.59	6.30	14.35	3.38	2.04	5.33	94.12	492.93	27.90	27.49	368.03	2.62	1.10	3.25
KTGRL-4	80.08	9.52	51.38	3.08	1.18	5.00	5.83	13.09	2.99	1.88	4.75	77.18	406.87	36.07	35.70	408.72	2.56	1.09	2.67
KTGRL-5	77.85	9.51	48.68	2.37	1.09	4.83	5.90	12.88	3.07	2.12	6.85	76.40	403.07	33.93	32.06	457.69	3.14	0.48	6.05
KTGRL-6	76.24	9.86	44.92	2.71	1.43	4.57	5.44	15.31	3.31	1.97	6.83	72.30	381.01	30.53	29.44	405.49	1.93	1.48	3.87
Agrifound Parvati (Check)	80.73	10.73	56.23	2.78	1.25	5.41	6.51	13.76	3.13	1.93	6.08	106.16	557.09	29.59	31.91	339.63	3.90	1.12	3.47
Mean	79.91	10.08	52.71	2.81	1.29	5.03	6.14	14.58	3.20	2.10	6.80	93.01	489.27	31.85	31.31	409.79	2.84	1.20	4.13
CV (%)	1.74	3.87	3.47	6.53	3.99	2.22	3.40	6.91	2.14	4.78	10.21	9.83	10.39	4.79	1.34	3.77	4.16	6.05	4.03
CD (p=0.05)	2.50	0.70	3.29	0.33	0.09	0.20	0.38	1.81	0.12	0.18	1.25	16.45	58.39	2.74	0.76	27.80	0.21	0.13	0.30

PH, Plant height (cm), NLPP, Number of leaves/plant; LL, Leaf length (cm); LW, Leaf width (cm); NT, Neck thickness (cm); BPD, Bulb polar diameter (cm); BED, Bulb equatorial diameter (cm); NCPB, Number of cloves/bulb; CL, Clove length (cm); CW, Clove width (cm); ACW, Average clove weight (g); ABW, Average bulb weight (g); BYPH, Bulb yield/hectare (q/ha); TSS, Total soluble solids (ºBrix); DM, Dry matter (%); TP, Total phenolics (µg gallic acid/g FW); CUPRAC, CUPric Reducing Antioxidant Capacity (µ mol trolox/g); FRAP, Fluorescence recovery after photobleaching (µ mol trolox/g); AA, Ascorbic acid (mg/100 g).

Table 2 Estimates of parameters of variability for different traits in long day garlic (Pooled data of 2022–23 and 2023–24)

Traits \ Parameters	PCV (%)			GCV (%)			h^2_{bs}			GA (%)		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
Plant height (cm)	4.63	3.78	3.83	4.13	3.24	3.42	79.65	73.35	79.41	7.59	5.72	6.27
Number of leaves/ plant	11.11	10.67	9.42	9.50	9.33	8.59	73.14	76.42	83.17	16.74	16.80	16.14
Leaf length (cm)	12.04	10.05	10.24	10.80	8.64	9.64	80.42	73.81	88.51	19.94	15.28	18.67
Leaf width (cm)	14.37	18.41	13.71	8.99	15.42	12.06	39.10	70.20	77.34	11.57	26.62	21.85
Neck thickness (cm)	12.72	11.96	10.90	9.95	9.72	10.14	61.18	66.04	86.60	16.04	16.27	19.44
Bulb polar diameter (cm)	9.75	9.49	8.90	8.45	8.97	8.62	75.12	89.24	93.75	15.09	17.45	17.20
Bulb equatorial diameter (cm)	8.45	10.32	7.45	6.73	6.25	6.63	63.51	36.66	79.23	11.05	7.79	12.16
Number of cloves/ bulb	18.06	13.77	12.24	9.86	11.32	10.10	29.78	67.53	68.15	11.08	19.16	17.18
Clove length (cm)	7.45	7.25	6.14	6.15	6.47	5.75	68.20	79.63	87.84	10.47	11.88	11.11
Clove width (cm)	13.70	11.84	10.87	11.23	6.91	9.76	67.16	34.01	80.63	18.96	8.30	18.05
Average clove weight (g)	26.67	29.36	25.53	20.93	27.48	23.40	61.58	87.63	84.01	33.83	52.99	44.18
Average bulb weight (g)	23.58	20.83	20.94	17.25	18.81	18.48	53.52	81.54	77.95	25.99	34.99	33.62
Bulb yield/hectare (q/ha)	23.58	20.81	20.99	17.25	18.38	18.24	53.52	77.98	75.51	25.99	33.43	32.64
Total soluble solids (°Brix)	12.13	8.53	10.06	9.40	7.96	8.84	60.14	87.26	77.33	15.02	15.32	16.02
Dry matter (%)	9.37	8.44	8.74	8.89	8.36	8.63	90.10	98.15	97.64	17.38	17.06	17.57
Total phenolics (µg gallic acid/g FW)	12.30	10.53	11.07	10.20	10.24	10.41	68.69	94.55	88.40	17.41	20.51	20.16
CUPRAC (µ mol trolox/g)	27.72	28.90	27.51	25.55	28.17	27.20	84.91	95.02	97.71	48.49	56.57	55.38
FRAP (µ mol trolox/g)	34.16	32.30	33.11	32.76	32.16	32.56	91.94	99.16	96.66	64.70	65.97	65.93
Ascorbic acid (mg/100 g)	32.29	32.78	31.85	30.18	32.33	31.60	87.35	97.26	98.40	58.09	65.68	64.56

PCV and GCV represent phenotypic and genotypic coefficients of variation, respectively; h^2_{bs}, Heritability in broad sense; GG, Genetic gain (%); CUPRAC, CUPric Reducing Antioxidant Capacity; FRAP, Fluorescence recovery after photobleaching.

and AA, which highlights the significance of additive gene action for the control of these traits and are more reliable for effective selection in garlic improvement. Comparable outcomes were noticed for ascorbic acid, yield per hectare, average bulb weight (Siddarth *et al.* 2022), total soluble solids (Dixit *et al.* 2023) and neck thickness (Tsega *et al.* 2010) in garlic.

Correlations and path-coefficient analyses: It may be possible to effectively utilize traits that have a strong and endearing bond in order to boost yield. When two opposing desirable traits that influence the principal trait need to be chosen, correlation can aid by demonstrating the degree of linkage with various traits. It also encourages the development of other features concurrently (Falconer 1981). Determining the attributes that are crucial for high yield as well as the degree and direction of the link between different variables and bulb yield would therefore be imperative. The correlation studies showed that at genotypic levels, bulb yield per hectare had significant positive association with PH, LL, LW, BED, NCPB, CW, ACW and ABW in pooled years. Earlier studies have also shown that the number of cloves per bulb (Dubey *et al.* 2010), clove width and average bulb weight (Dixit *et al.* 2021b) had significantly positive association with bulb yield per hectare. Further, CW, ACW, NCPB, ABW and BED were found to have significant positive correlation with each other (Table 3). Additionally, a closer look at the correlation coefficients revealed that CW, ABW and BYPH all have significantly positive correlation with plant height, leaf length, and leaf width. Tsega *et al.* (2010) have also observed similar association of plant height and leaf length with yield/plant. Correlation studies and their coefficients of determination support the conclusion that when distinguishing genotypes with high bulb yield/plant, factors such as PH, LL, LW, BED NCPB, CW, ACW and ABW should be taken into account. Over time, most of these characteristics exhibited a consistent association, underscoring their significance for garlic improvement projects.

Correlation analysis reveals the pattern of relationships between yield and its constituent qualities, indicating reliance. While, path-coefficient predicts the cause-effect relationship and makes prudent choices. In the present study, the dependent variable was BYPH, while the causative variables were all the other features. A review of data revealed both genotypic direct and indirect effects (Supplementary Table 2). BYPH was most positively and directly impacted by ABW (0.920). NCPB (0.058), BPD (0.044), LL (0.039), CW (0.035) and PH (0.013), which made direct contributions to the overall relationship with BYPH in pooled years. Prior research has also demonstrated the positive and direct effects of a variety of characteristics on bulb yield/ha, including plant height and clove width (Kumari *et al.* 2021), the number of cloves/bulb, bulb polar diameter and bulb weight (Chotaliya and Kulkarni 2017). At the genotypic level, the amount of unexplained variation for BYPH was very low (-0.00098), suggesting that characteristics examined in this study accounted for a sizable amount of the variation in the dependable variation i.e. BYPH. Therefore, selection based on average bulb weight, number of cloves/bulb, bulb polar diameter, leaf length and clove weight would be a fruitful strategy for yield improvement in garlic. Further, association among the different quality traits revealed that TSS has high positive correlation with dry matter content followed by TP, besides this TP were also found to have positive association with ascorbic acid (Fig. 1).

Table 3 Estimates of genotypic correlation coefficients for different traits in long day garlic in pooled years

Traits	PH	NLPP	LL	LW	NT	BPD	BED	NCPB	CL	CW	ACW	ABW
NLPP	-0.216											
LL	0.958*	0.151										
LW	0.678*	-0.614*	0.342									
NT	-0.168	0.592*	-0.025	0.056								
BPD	0.306	0.750*	0.636*	-0.407	0.084							
BED	0.771*	0.240	0.872*	0.347	0.097	0.414						
NCPB	0.335	-0.164	0.124	0.675*	0.649*	-0.490*	0.464*					
CL	0.163	0.445*	0.324	-0.365	0.656*	0.510*	0.017	0.190				
CW	0.683*	-0.360	0.512*	0.456*	0.095	-0.261	0.606*	0.795*	0.204			
ACW	0.540*	-0.541*	0.294	0.532*	0.086	-0.492*	0.414	0.885*	0.108	0.987*		
ABW	0.911*	0.173	0.952*	0.465*	0.186	0.407	0.978*	0.453*	0.343	0.697*	0.595*	
BYPH	0.919*	0.160	0.951*	0.482*	0.182	0.393	0.958*	0.459*	0.334	0.710*	0.606*	0.987*

*Significant at $p \leq 0.05$. PH, Plant height (cm), NLPP, Number of leaves/plant; LL, Leaf length (cm); LW, Leaf width (cm); NT, Neck thickness (cm); BPD, Bulb polar diameter (cm); BED, Bulb equatorial diameter (cm); NCPB, Number of cloves/bulb; CL, Clove length (cm); CW, Clove width (cm); ACW, Average clove weight (g); ABW, Average bulb weight (g); BYPH, Bulb yield/hectare (q/ha).

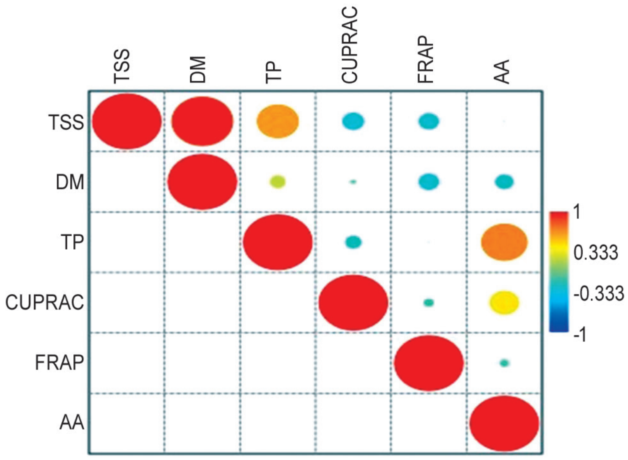

Fig. 1 Genotypic correlation coefficients for different quality traits of long day garlic genotypes (Pooled data of 2022–23 and 2023–24).
TSS, Total soluble solids (ºBrix); DM, Dry matter (%); TP, Total phenolics (μg gallic acid/g FW); CUPRAC, CUPric Reducing Antioxidant Capacity (μ mol trolox/g); FRAP, Fluorescence recovery after photobleaching (μ mol trolox/g); AA, Ascorbic acid (mg/100 g).

Principal component analysis: Principal component analysis (PCA) was used to demonstrate the importance of the significant contribution to the overall variance (Table 4). It indicated that a total of seven components account for the maximum estimated variation (100.00%). The variables with the highest impact, accounting for 25.00% of the overall variation, were NT, AA, CW and ACW, according to the variable loadings of PC I. In PC II, the main characteristics that accounted for 20.00% of the overall variation were AA, NCPB, TSS, BYPH and LL. Using PCA, Sharma *et al.* (2018), Aswani *et al.* (2024), Pasupula *et al.* (2024), Kaushal *et al.* (2025), found significant genetic variation in their breeding material. Further, loading of different genotypes on the basis of first two principal components (Fig. 2) indicated that the genotype 'KTGRL-1' and 'KTGRL-2' are the major contributors to divergence between different genotypes of garlic, whereas contribution of 'KTGRL-4' and 'KTGRL-6' was found least in divergence.

The genotype, 'KTGRL-1' followed by 'KTGRL-2', were found most promising based on their performance for different traits under study. Further, parameters of variability revealed that selection should be made on the

Table 4 Principal component analysis for different traits in long day garlic in pooled years

Traits \ Components	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	PC_7
Plant height (cm)	-0.06	-0.08	-0.85	-0.17	-0.24	0.19	-0.02
Number of leaves/plant	-0.65	-1.49	0.67	0.77	2.92	-1.04	-0.09
Leaf length (cm)	-1.16	0.44	0.55	-0.21	-1.16	-2.55	-0.29
Leaf width (cm)	-0.13	0.02	-0.83	-0.52	0.15	0.05	-0.29
Neck Thickness (cm)	2.97	0.36	2.13	-0.22	-0.19	-0.18	-1.13
Bulb polar diameter (cm)	0.03	-0.10	-0.51	-0.51	0.28	0.01	-1.10
Bulb equatorial diameter (cm)	-0.11	-0.09	-0.73	-0.75	0.00	0.12	-0.58
Number of cloves per bulb	-1.95	1.58	2.08	0.39	-0.85	-0.05	0.39
Clove length (cm)	-0.17	0.08	-0.45	-0.62	-0.27	-0.29	-0.86
Clove width (cm)	1.11	-0.33	0.62	-1.47	0.34	-0.69	2.86
Average clove weight (g)	0.31	-1.40	-0.10	0.94	-2.24	1.20	0.84
Average bulb weight (g)	-0.23	-0.01	-0.62	-0.73	-0.11	-0.15	-0.38
Bulb yield/hectare (q/ha)	-0.78	0.72	1.27	-0.27	1.13	2.73	-0.17
Total soluble solids (°Brix)	0.11	1.24	-1.18	1.17	0.62	0.18	2.04
Dry matter (%)	-0.17	-0.08	-0.72	-0.75	0.06	0.22	-0.52
Total phenolics (μg gallic acid/g FW)	-0.27	-2.31	0.55	1.90	-0.46	-0.02	-0.14
CUPRAC (μ mol trolox/g)	-0.21	-0.25	-0.45	-0.38	-0.26	0.75	-0.39
FRAP (μ mol trolox/g)	0.19	-0.15	-0.44	-0.93	-0.02	-0.02	0.37
Ascorbic acid (mg/100 g)	1.17	1.84	-0.99	2.34	0.30	-0.45	-0.56
Eigen values	1.73	1.43	1.17	0.98	0.81	0.57	0.33
Total variance (%)	25.00	20.00	17.00	14.00	12.00	8.00	5.00
Cumulative variation (%)	25.00	45.00	62.00	76.00	87.00	95.00	100.00

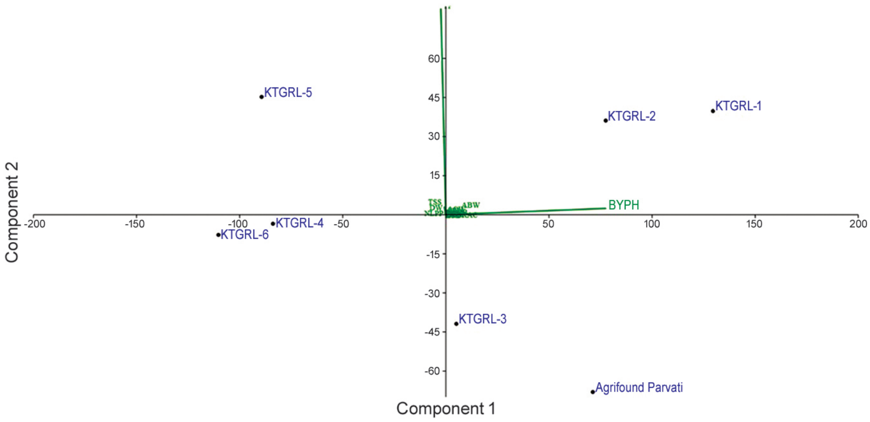

Fig. 2 Loading of seven genotypes of long day garlic based on first two principal components (Pooled data of 2022–23 and 2023–24).

basis of leaf width, average clove and bulb weight, bulb yield/ha, total phenolics, CUPRAC, FRAP and ascorbic acid for yield improvement in garlic. The correlation studies indicated that bulb yield/ha had significantly positive association with plant height, leaf length and width, bulb equatorial diameter, number of cloves/bulb, clove width, average clove and bulb weight. Further, path-analysis revealed that selection on the basis of average bulb weight, number of cloves/bulb, bulb polar diameter, leaf length, clove weight and plant height would be a fruitful strategy for yield improvement in garlic.

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