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RESEARCH ARTICLE

Genetic variability and correlation studies in cabbage (*Brassica oleracea* var. *capitata* L.) genotypes

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Abstract

The study was carried out using a randomized complete block design with 3 replications for each genotype at the Research Farm of the Department of Vegetable Science, Dr Yashwant Singh Parmar University of Horticulture and Forestry (YSP UHF), Nauni, Solan, Himachal Pradesh during the rabi seasons over 2 consecutive years. The evaluation focused on various morphological and quality traits to assess genetic variability and potential for improvement in cabbage. Among the traits studied, stalk length exhibited high phenotypic and genotypic coefficients of variability, while both stalk length and core length displayed high heritability along with substantial genetic gain. Correlation studies revealed that net head weight showed significant positive associations with plant height, gross head weight, equatorial diameter, polar diameter, head shape index, total soluble solids and ascorbic acid content. Further, path coefficient analysis indicated that gross head weight, plant height and polar diameter had the most direct effects on net head weight at the genotypic level, suggesting that selection for these traits would be effective in improving cabbage yield. Genetic divergence analysis grouped 23 diverse cabbage genotypes into 6 clusters, with the majority of genotypes concentrated in clusters II, V and VI, reflecting substantial variability among the germplasms. The maximum inter-cluster distance was observed between clusters II and III, highlighting that hybridisation between genotypes from these clusters could produce promising recombinants or superior hybrids. Overall, the study provides valuable insights into the inheritance of key traits and identifies potential parents for breeding programs aimed at enhancing yield, quality and overall performance in cabbage.

Keywords: correlation; genetic advance; heritability; path analysis; Mahalanobis D^2

Introduction

Cabbage (*Brassica oleracea* var. *capitata* L.) is a member of the Cole crop group and is believed to have originated from a single wild ancestor, *Brassica sylvestris*, commonly known as wild cabbage, cliff cabbage, or "Colewart." Its evolution involved mutation, introgression from wild relatives, human selection and adaptation. White-headed cabbage (*B. oleracea*) has its evolutionary origin in non-heading leafy forms native to the eastern Mediterranean and Asia Minor from where it gradually spread to Europe, where head-forming types were later developed (1). At present, cabbage is among the most extensively cultivated vegetable crops worldwide due to its wide adaptability, consistent productivity and availability throughout the year. The crop thrives best under cool and humid climatic conditions, requiring moderate temperatures and adequate soil moisture for proper vegetative growth and head formation. The mid-hill agro-climatic conditions of Solan, Himachal Pradesh, characterised by mild temperatures, high seasonal rainfall and fertile, well-drained soils with good organic matter content, provide a highly suitable environment for cabbage cultivation. In this region, cabbage is predominantly grown under open-field conditions during rabi season, while staggered planting and altitude-based cultivation enable extended market availability. Owing to its desirable taste, culinary versatility and high nutritive value, cabbage occupies an important place among cole crops. The edible head is mainly consumed as a fresh vegetable and is also processed into fermented and pickled products. From a nutritional standpoint, cabbage serves as a rich source of vitamin C, B-complex vitamins, potassium and calcium (2). Beyond its dietary value, cabbage exhibits notable medicinal properties. Both the American Cancer Society and the National Research Council recommend increasing cabbage consumption to reduce the risk of certain types of cancer (3). The plant is thought to possess a strong antioxidative defence system capable of neutralising harmful free radicals such as O_2-, OH and HCO_3-, which are produced during normal metabolic processes and in response to environmental stresses. This combination of nutritional and therapeutic attributes makes cabbage a vital vegetable in human diets worldwide.

The rising popularity of cabbage, owing to its adaptability, affordability, year-round availability and importance in the fast-food industry, underscores the need for focused breeding efforts aimed at its genetic improvement. Effective crop improvement requires an understanding of the magnitude of variability present in a given environment, as this forms the basis for an efficient breeding program. Heritability serves as an important measure to estimate the extent to which environmental factors influence genotype expression. However, it is often challenging to distinguish between heritable and non-heritable components of variability. To address this, a biometrical approach is employed to partition observed variability into heritable and non-heritable components by estimating genetic parameters such as the genetic coefficient of variation, heritability and genetic advance. While phenotypic variability among germplasm provides an indication of potential genotypic variability, quantitative traits are highly influenced by environmental conditions. Therefore, selecting traits for breeding should consider the degree of variability along with heritability and expected genetic gain. Moreover, the efficiency of selection can be enhanced by understanding the relationships among traits and yield, which can be quantified through correlation coefficient analysis (4). In light of these considerations, the present study was undertaken to evaluate the extent of genetic variability among cabbage genotypes and to determine the inter-relationships among various horticultural traits. The findings are expected to provide valuable insights for selecting superior genotypes and devising effective breeding strategies aimed at improving yield and quality in cabbage.

Material and Method

Study area and plant material

The study “Genetic variability and correlation studies in cabbage (*Brassica oleracea* var. *capitata* L.) genotypes” was conducted at the Experimental Farm of the Department of Vegetable Science, Dr. YSP UHF, Nauni, Solan, Himachal Pradesh during the rabi season for 2 consecutive years (2018, 2019). The farm, located at 30°51′ N latitude and 77°11′ E longitude at 1270 m above sea level, experiences mild summers, cool winters and moderate rainfall (1000–1300 mm). The mean temperature was 12.76 °C with rainfall and relative humidity of 35.48 mm and 57 % for the consecutive years. The sandy loam soil with pH of 6–7 gives more yield. A total of 23 diverse cabbage genotypes developed in UHF, Nauni, including the check cultivar Pride of India, were evaluated for variability in morphological and horticultural traits. The genotypes and their sources are listed in Table 1 and the crop appearance is shown in Fig. 1. The study aimed to assess genetic variability, heritability and trait inter-relationships to identify superior genotypes for breeding programs.

Experimental design

The experimental field was divided into 69 plots and treatments were randomly assigned using a random number table. A total of 23 cabbage genotypes were planted in plots measuring 1.8 × 1.8 m with 3 replications, following a randomized complete block design (RCBD) and maintaining a spacing of 45 × 30 cm.

Nutrient application and cultural management

The seeds of all cabbage genotypes were sown in the experimental farm in seed beds measuring 1 × 1 × 0.15 m under careful management. Prior to sowing, the soil was well-prepared to ensure good tilth, promoting vigorous seedling growth. Weeds, stubbles and dried roots from previous crops were removed and well-decomposed farmyard manure (FYM) was applied at 5 kg m^2. Healthy, uniform seedlings of 15–20 days old were carefully uprooted from the seed beds, 1 hr after watering to minimise root damage and transplanted into the main field at the recommended spacing. Transplanting was carried out in the afternoon, with additional seedlings planted along plot borders for gap filling if required. The irrigation practice was done twice a week. Standard intercultural operations, including irrigation, hoeing, gap filling and plant protection measures, were performed following the package of practices for vegetable cultivation issued by the Directorate of Extension Education, University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh.

Table 1. List of genotypes along with their sources

Sl. No.	Genotypes	Sl. No.	Source
1.	UHF CAB-1	13	UHF CAB-13
2.	UHF CAB-2	14	UHF CAB-14
3.	UHF CAB-3	15	UHF CAB-15
4.	UHF CAB-4	16	UHF CAB-16
5.	UHF CAB-5	17	UHF CAB-17
6.	UHF CAB-6	18	UHF CAB-18
7.	UHF CAB-7	19	UHF CAB-19
8.	UHF CAB-8	20	UHF CMS CAB-20
9.	UHF CAB-9	21	UHF CMS CAB-21
10.	UHF CAB-10		UHF CMS CAB-22
11.	UHF CAB-11		Pride of India – Check variety
12.	UHF CAB-12		

Fig. 1. Cabbage crop at experimental farm, Department of Vegetable Science, Nauni.

Plant growth and yielding traits

Observations were recorded from 5 randomly selected plants in each replication and the mean values were calculated for statistical analysis. The characters evaluated included: plant height (cm), days to 50 % marketable maturity, number of non-wrapper leaves, stalk length (cm), gross head weight (g), net head weight (g), equatorial and polar diameters of the head (cm), head shape index, head compactness (g cm^{-3}), core length (cm), yield per plot (kg) and per hectare (q), total soluble solids (°B), ascorbic acid content (mg 100 g^{-1}) and incidence of insect pests and diseases.

Statistical analysis

The mean data for various traits were analysed using the RCBD with the help of MS Excel and OPSTAT (5). The results were interpreted based on the 'F' test and critical differences (CD) were calculated at the 5 % level of significance. Parameters of variability were estimated following the formulas of Burton and DeVane (6). Broad-sense heritability was computed according to Burton and DeVane (6) and Allard (7). The expected genetic advance from selecting the top 5 % of superior individuals was calculated as per Allard (7) and genetic gain, expressed as the percentage of genetic advance relative to the population mean, was determined using the method of Johnson et al. (8). Path coefficient analysis was performed following the procedure suggested by Wright (9) and further elaborated by Dewey and Lu (10).

Results and Discussion

The magnitude of variability, genotypic and phenotypic coefficients of variation were computed and are shown in Table 2. For all quantitative and qualitative traits, the phenotypic coefficient of variability (PCV) values was higher than the corresponding genotypic coefficients of variability (GCV), indicating that the observed variation is influenced not only by genetic factors but also by environmental conditions (11). The magnitude of variability differed among traits, ranging from low (<15 %) to moderate (15–30 %) and high (> 30 %), reflecting substantial diversity among the genotypes studied (12). A high GCV suggests considerable genetic variability for the trait, which is advantageous for effective selection (13). Similarly, a high PCV indicates a greater potential for selection, as it reflects the overall variation present in the trait, encompassing both genetic and environmental influences (14). These results highlight the presence of significant variability in the experimental material, providing opportunities for the selection and improvement of desirable traits in cabbage. As can be perused from Table 2, the PCV in our present investigation was high for only one trait i.e., stalk length while, it was moderate for core length, head compactness, plant height, gross head weight, net head weight and low for ascorbic acid, no. of non-wrapper leaves, total soluble solids, head shape index, equatorial diameter of head, polar diameter of head and days to 50 % marketable maturity. Similarly, the GCV were high for stalk length, moderate for core length, head compactness, plant height, gross head weight and low for ascorbic acid, net head weight, non-wrapper leaves, total soluble solids, polar diameter, head shape index, equatorial diameter of head and days to 50 % marketable maturity. In an earlier study, high PCV and GCV observed for stalk length and moderate for core size, plant height and head shape index (15). In a recent study, moderate PCV and GCV observed for gross head weight and low for equatorial diameter, head shape index, non-wrapper leaves and polar diameter in cabbage crop (16). High heritability (> 80 %) was estimated for core length, stalk length and plant height and total soluble solids. This suggests that a significant portion of the observed phenotypic variance is attributable to genetic factors, indicating that reliable selection for these traits can be effectively based on their phenotypic expression. Moderate heritability (50–80 %) was recorded for days to 50 % marketable maturity ascorbic acid content, gross head weight, polar diameter of head, head compactness and non-wrapper leaves, which indicates a considerable influence of environment on the expression of above mentioned 6 traits. Low values of heritability were recorded for equatorial diameter of head; net head weight and head shape index. Corroborating with the result of present investigation, earlier results estimated moderate heritability for non-wrapper leaves (17). Previous works also estimated heritability in broad sense to be high for plant height, core length and stalk length and moderate for ascorbic acid content (15). Further works observed high heritability for core length in and moderate for polar diameter of head and length of stalk in cabbage (18). Previous works estimated high heritability for plant height (19). Recent works observed moderate heritability for polar diameter of head, non-wrapper leaves and equatorial diameter of head (16). A higher heritability indicates that genotypic factors play a major role in the expression of a trait. According to previous results, traits with low heritability are less reliable for selection because their expression is largely influenced by environmental factors (7). The effectiveness of selection depends on the magnitude of heritability and the expected progress is directly related to genetic advance. Therefore, traits exhibiting both high heritability and high genetic advance respond more effectively and rapidly to selection.

Table 2. Estimates of phenotypic and genotypic coefficients of variability, heritability, genetic advance and genetic gain of different characters in cabbage

Characters	Coefficient of variation (%)		Heritability (%)	Genetic advance	Genetic gain
	phenotypic coefficient of variability (PCV)	genotypic coefficient of variability (GCV)			
Plant height (cm)	18.67	17.46	87.50	9.43	33.67
Days to 50 % marketable maturity	4.95	4.38	78.20	6.34	7.97
Non-wrapper leaves	13.11	9.80	55.80	1.95	15.08
Head compactness	22.75	18.52	66.20	15.34	31.05
Gross head weight (g)	18.07	15.29	71.60	365.71	26.65
Net head weight (g)	15.74	10.09	41.10	83.64	13.33
Equatorial diameter of head (cm)	9.40	6.40	46.63	1.02	8.98
Polar diameter of head(cm)	9.20	7.59	68.10	9.20	12.91
Stalk length(cm)	36.47	34.68	90.40	2.05	67.95
Core length (cm)	28.74	27.98	94.80	3.40	56.13
Head shape index	10.13	6.45	40.60	0.07	8.46
Total soluble solids (°Brix)	12.75	11.89	86.90	1.28	22.83
Ascorbic acid (mg 100 g^{-1})	14.98	12.89	74.10	2.69	22.86

Analysis of the data presented in Table 2 showed that genetic gain, expressed as a percentage of the population mean, varied from 7.97 % to 67.95 % across the different traits studied. It was found high for the traits viz., stalk length, core length, moderate was for plant height, head compactness, gross head weight, ascorbic acid content and total soluble solids (TSS), while it was low for non-wrapper leaves, net head weight, polar diameter of head, equatorial diameter of head, head shape index and days to 50 % marketable maturity. Traits exhibiting high heritability along with high genetic advance are primarily governed by additive gene effects, making selection based on phenotypic performance effective for their improvement, as suggested by earlier results (20). In the present study, stalk length and core length showed high heritability coupled with high genetic advance, while plant height and TSS exhibited high heritability with moderate genetic advance. These results indicate that these traits are largely controlled by additive genes and therefore, selection would be effective for their enhancement, consistent with the findings of previous researchers (16).

Correlation studies

Correlation coefficients were estimated at both phenotypic and genotypic levels and are presented in Table 3. In general, genotypic correlations were higher than phenotypic correlations, indicating strong genetic associations between traits. However, in some cases, such as non-wrapper leaves, phenotypic correlation slightly exceeded genotypic correlation, suggesting that environmental factors also influenced the observed association. In this study, analysis of 13 important traits revealed that net head weight had significant positive correlations at both genotypic and phenotypic levels with gross head weight, plant height, polar diameter of head, TSS, head shape index, ascorbic acid content and equatorial diameter of head. These results highlight the key traits that contribute to the improvement of net head weight in cabbage breeding programs.

Significant negative correlations at both genotypic and phenotypic levels of net head weight were observed with days to 50 % marketable maturity. As for ascorbic acid content, it had significant positive correlation at both genotypic and phenotypic levels with TSS, stalk length, gross head weight. It has significant negative correlations at both genotypic and phenotypic levels with days to 50 % marketable maturity. The TSS was significantly and positively correlated with plant height, gross head weight and significantly negative correlation with days to 50 % marketable maturity. Core length had significant positive correlation at genotypic and phenotypic level with equatorial diameter of head, polar diameter of head, stalks length and had significantly negative correlation with head compactness. Head compactness had significant positive correlation at genotypic level with days to 50 % marketable maturity, while it had significant negative correlation at both genotypic and phenotypic level with equatorial diameter of head and polar diameter of head. Head shape index had significant positive genotypic and phenotypic correlation with polar diameter of head and gross head weight, had negative correlation with non-wrapper leaves and days to 50 % marketable maturity. Polar diameter of head had significant positive correlation with gross head weight, equatorial diameter of head, plant height, had negative correlation with days to 50 % marketable maturity and non-wrapper leaves. Equatorial diameter of head had significant positive genotypic and phenotypic correlation with non-wrapper leaves. Gross head weight had significant positive correlation with plant height and significant negative correlation for days to 50 % marketable maturity. Days to 50 % marketable maturity had significant negative correlation with plant height.

The findings of correlation studies concluded in the present study are in the conformity of earlier researchers. The yield displayed positive and significant correlation with all the characters except stalk length as in investigation (21). Early works reported that equatorial diameter had negative but non-significant correlation with days to maturity (15) and the positive and significant correlation of ascorbic acid content with plant spread, number of non-wrapper leaves, head weight, head polar diameter and equatorial diameter (18). The head weight had the highest significant positive correlation with yield ($r = 0.927^{**}$), while days to maturity showed a negative association with all traits studied (22). This negative correlation suggests that selecting early maturing cabbage genotypes can help improve yield, which aligns with the findings of the present study. Previous works evaluated 31 genetically diverse tropical cabbage genotypes and found that net head weight was significantly positively correlated with days to harvest, plant spread, gross plant weight, head width, stalk length and the number of wrapper and non-wrapper leaves (23). Similarly, at the phenotypic level, marketable head yield per plot had significant positive correlations with net head weight gross head weight, equatorial diameter, marketable heads per plot and polar diameter of the head (24). These studies collectively highlight the importance of head weight and related traits in determining yield and inform selection strategies in cabbage breeding programs.

Path coefficient analysis

The phenotypic and genotypic path coefficients, showing direct and indirect effects of key traits on net head weight, are presented in Tables 4 and 5. At the phenotypic level (Table 4), gross head weight had the highest positive direct effect on net head weight, followed by plant height. In contrast, days to 50 % marketable maturity, equatorial diameter, polar diameter, ascorbic acid, head shape index and TSS showed negative direct effects. Regarding indirect effects, plant height positively influenced net head weight through gross head weight and days to 50 % marketable maturity. Meanwhile, days to 50 % marketable maturity had a positive indirect effect on net head weight via polar diameter, but a negative indirect effect through gross head weight. These results highlight the complex interplay of traits affecting net head weight, indicating that selection based on both direct and indirect contributors can improve yield more effectively in cabbage breeding programs. Further, equatorial diameter of head had positive indirect effect through gross head weight whereas, it had negative indirect effect through polar diameter of head. Polar diameter of head had positive indirect effect on net head weight through gross head weight followed by days to 50 % marketable maturity. Whereas, it had negative indirect effects through equatorial diameter of head. Head shape index had positive indirect effects on net head weight through gross head weight whereas, it had negative indirect effects through polar diameter of head. The TSS had positive indirect effect on net head weight through gross head weight followed by days to 50 % marketable maturity. Whereas, it had negative indirect effects through ascorbic acid content. Ascorbic acid content had positive indirect effect on net head weight through gross head weight. Whereas negative indirect effect through polar diameter of head.

Table 3. Estimates of genotypic and phenotypic correlation coefficients between different characters in cabbage

Characters		Plant height (cm)	Days to 50 % marketable Maturity	Non–wrapper leaves	Stalk length (cm)	Gross head weight (g)	Equatorial diameter of head (cm)	Polar diameter of head (cm)	Head shape index	Head compactness (g cm^{-3})	Core length (cm)	TSS (°Brix)	Ascorbic acid (mg 100 g^{-1})	Net head weight (g)
Plant height (cm)	G	1.000	-0.343*	-0.353*	-0.090	0.699*	0.397*	0.545*	0.274*	-0.249*	0.150	0.396*	0.174	0.819*
	P		-0.288*	-0.173	-0.077	0.584*	0.205	0.422*	0.224	-0.146	0.129	0.342*	0.125	0.526*
Days to 50 % marketable maturity	G			0.334*	0.213	-0.370*	-0.068	-0.526*	-0.690*	0.316*	-0.080	-0.485*	-0.485*	-0.577*
	P			0.063	0.166	-0.269*	-0.075	-0.401*	-0.320*	0.204	-0.051	-0.389*	-0.373*	-0.379*
Non–wrapper leaves	G				-0.024	-0.217	0.405*	-0.429*	-0.730*	0.086	0.091	0.136	0.025	-0.217
	P				-0.015	0.050	0.274*	-0.294*	-0.488*	0.067	0.034	0.070	0.003	0.172
Stalk length (cm)	G					-0.096	0.039	-0.141	-0.134	-0.056	0.282*	-0.207	0.331*	-0.171
	P					-0.100	-0.003	-0.102	-0.044	-0.057	0.263*	-0.190	0.254*	-0.133
Gross head weight (g)	G						0.467*	0.713*	0.418*	-0.177	0.132	0.372*	0.308*	0.989*
	P						0.235	0.475*	0.269*	-0.032	0.121	0.273*	0.280*	0.804*
Equatorial diameter of head (cm)	G							0.607*	-0.125	-0.800*	0.485*	0.218	0.243*	0.247*
	P							0.280*	-0.533*	-0.697*	0.380*	0.235	0.141	0.052
Polar diameter of Head (cm)	G								0.734*	-0.746*	0.433*	0.125	0.317*	0.581*
	P								0.567*	-0.626*	0.353*	0.096	0.184	0.317*
Head shape index	G									-0.228	0.037	0.076	0.264*	0.494*
	P									0.050	-0.001	-0.042	0.143	0.269*
Head compactness	G										-0.581*	-0.043	-0.306*	0.012
	P										-0.504*	-0.099	-0.171	0.157
Core length (cm)	G											0.021	0.233	-0.056
	P											0.023	0.222	-0.041
TSS (°Brix)	G												0.451*	0.527*
	P												0.380*	0.239*
Ascorbic acid (mg 100 g^{-1})	G													0.322*
	P													0.168

Table 4. Path coefficient analysis showing the direct and indirect effect of different characters on net head weight (g) in cabbage at phenotypic level

Characters	Plant height (cm)	Days to 50 % marketable maturity	Gross head weight (g)	Equatorial diameter of head (cm)	Polar diameter of head (cm)	Head shape index	TSS (° Brix)	Ascorbic acid Content (mg 100 g^{-1})	Phenotypic correlation (r_p) with net head weight (g)
Plant height (cm)	0.084	0.075	0.486	-0.031	-0.051	-0.012	-0.011	-0.013	0.526*
Days to 50 % marketable Maturity	-0.024	-0.261	-0.223	0.011	0.048	0.017	0.012	0.040	-0.379*
Gross head weight (g)	0.049	0.070	0.832	-0.035	-0.057	-0.015	-0.008	-0.030	0.804*
Equatorial diameter of head(cm)	0.017	0.019	0.195	-0.152	-0.033	0.029	-0.007	-0.015	0.052*
Polar diameter of head (cm)	0.035	0.104	0.395	-0.042	-0.121	-0.031	-0.003	-0.019	0.317*
Head shape index	0.018	0.083	0.223	0.081	-0.068	-0.055	0.001	-0.015	0.269*
TSS(°Brix)	0.028	0.101	0.226	-0.035	-0.011	0.002	-0.032	-0.040	0.239*
Ascorbic acid content	0.010	0.097	0.232	-0.021	-0.022	-0.007	-0.012	-0.107	0.168*

Residual factor = 0.274 ; r_p = phenotypic correlation coefficient; diagonal bold values are direct effects.

At genotypic level, gross head weight showed high positive direct effect on net head weight followed by polar diameter of head, plant height and TSS (Table 5). Whereas, equatorial diameter of head followed by head shape index, days to 50 % marketable maturity, ascorbic acid content showed negative direct effect on net head weight. Plant height had positive indirect effect on net head weight through gross head weight followed by polar diameter of head and days to 50 % marketable maturity. While negative indirect effect through equatorial diameter of head followed by head shape index. Days to 50 % marketable maturity had positive indirect effects on net head weight through head shape index while negative indirect effect through gross head weight. Gross head weight had positive indirect effect on net head weight through polar diameter of head followed by plant height and days to 50 % marketable maturity, while it had negative indirect effect through equatorial diameter of head and head shape index. Equatorial diameter of head had positive indirect effect on net head weight through gross head weight followed by polar diameter of head. Polar diameter of head had positive indirect effect on net head weight through gross head weight followed by days to 50 % marketable maturity and plant height, while it had negative indirect effect through head shape index followed by equatorial diameter of head. Head shape index had positive indirect effect on net head weight through gross head weight followed by days to 50 % marketable maturity and polar diameter of head, while it had negative indirect effect through ascorbic acid content. The TSS had positive indirect effect on net head weight through gross head weight followed by days to 50 % marketable maturity. While, it had negative indirect effects through equatorial diameter of head. Ascorbic acid had positive indirect effect on net head weight through gross head weight followed by days to 50 % marketable maturity. While it had negative indirect effect through equatorial diameter of head followed by head shape index. The days to maturity had direct negative effect on yield (25). Previous works also reported positive correlation of frame spread with polar diameter, equatorial diameter, gross weight and net weight of head (26). The head weight had the highest positive direct effect on yield (18). Consistent with the present study, early results reported that head weight exerted the highest positive direct effect on yield (22). Supporting these findings, a negative direct effect of ascorbic acid content on cabbage yield (15). Similarly, the maximum negative direct effects were associated with gross head weight and head shape index (24). These studies collectively highlight the varying contributions of different traits to yield and emphasise the importance of selecting traits with strong positive direct effects in breeding programs.

Genetic divergence

The analysis of variance revealed highly significant differences among the 23 cabbage genotypes for 13 yield and component traits, indicating substantial variability and justifying further genetic divergence analysis (25). Mahalanobis D^2 statistic was employed to estimate genetic divergence using all traits, as it allows precise comparison among all possible pairs of genotypes and facilitates identification of potential parental combinations for hybridisation, a method widely applied in cabbage studies (27, 28). Based on the performance of different traits, the 23 genotypes were grouped into 6 clusters (I–VI) as presented in Table 4. Cluster V contained the highest number of genotypes (8), followed by cluster II (6), cluster VI (5) and cluster IV (2), while clusters I and III had only one genotype each. Genotypes within the same cluster were genetically more homogeneous. Similar clustering of cabbage genotypes based on genetic divergence has been reported (15, 25) and comparable studies have been conducted in cauliflower (29–33) and kale (14).

The intra- and inter-cluster distances (D^2) are presented in Table 5. Intra-cluster distance was highest in cluster I and lowest in cluster VI, indicating considerable genetic heterogeneity within cluster I. The maximum inter-cluster distance was observed between clusters II and III, suggesting wide genetic divergence, while the minimum distance was between clusters I and II, indicating close similarity. Cluster means for various horticultural traits were further analysed to confirm conformity and are presented in Table 6.

The cluster-wise performance of cabbage genotypes for growth and yield traits showed considerable variation. Plant height was highest in cluster I, followed by cluster V, cluster II, cluster IV, cluster III and cluster VI (Table 7). Marketable maturity was earliest in clusters II and V, followed by cluster I, with delayed maturity in clusters VI, IV and III. The number of non-wrapper leaves increased from cluster VI to cluster IV. Stalk length varied from cluster V to cluster II. For head traits, the equatorial diameter was highest in cluster IV and lowest in cluster III, while polar diameter ranged from cluster VI to cluster III. Head shape index was maximum in cluster I and minimum in cluster IV. Head compactness was greatest in cluster V and lowest in cluster VI. Gross head weight was highest in cluster I and lowest in cluster III, while net head weight followed a similar trend, with the highest in cluster I and lowest in clusters III and IV. Core length was shortest in cluster V and longest in cluster I. Total soluble solids (°Brix) were highest in cluster II and lowest in cluster III, whereas ascorbic acid content (mg 100 g^{1}) was maximum in cluster II and minimum in cluster III. These variable cluster means for growth and yield traits align with observations reported by many researchers in cabbage, cauliflower and kale (Table 8) (29, 30, 33, 28, 14).

Table 5. Path coefficient analysis showing the direct and indirect effect of characters on net head weight (g) in cabbage at genotypic level

Characters	Plant height (cm)	Days to 50 % marketable maturity	Gross head weight (g)	Equatorial diameter of head (cm)	Polar diameter of head (cm)	Head shape index	TSS (° Brix)	Ascorbic acid content (mg 100^{-1})	Genotypic correlation (r_g) with net head weight (g)
Plant height (cm)	0.205	0.129	0.670	-0.212	0.150	-0.133	0.017	-0.006	0.819*
Days to 50 % marketable maturity	-0.070	-0.377	-0.354	0.036	-0.145	0.335	-0.020	0.019	-0.577*
Gross head weight (g)	0.143	0.139	0.958	-0.250	0.196	-0.202	0.016	-0.012	0.989*
Equatorial diameter of head(cm)	0.081	0.025	0.448	-0.535	0.167	0.060	0.009	-0.009	0.247*
Polar diameter of head (cm)	0.111	0.198	0.683	-0.324	0.275	-0.356	0.005	-0.012	0.581*
Head shape index	0.056	0.260	0.400	0.066	0.202	-0.485	0.003	-0.010	0.494*
TSS (°Brix)	0.081	0.183	0.356	-0.116	0.034	-0.036	0.043	-0.018	0.527*
Ascorbic acid content	0.035	0.183	0.295	-0.130	0.087	-0.128	0.019	-0.040	0.322*

Residual factor = -0.131; r_g = genotypic correlation coefficient; diagonal bold values are direct effect.

Table 6. Clustering pattern of 23 genotypes of cabbage on the basis of genetic divergence

Cluster	Number of genotypes	Name of genotypes
I	1	UHF CMS CAB-21
II	6	UHF CAB-2, UHF CAB-8, UHF CAB-9, UHF CAB-13, UHF CAB-14, UHF CAB-18
III	1	UHF CAB-15
IV	2	UHF CAB-7, UHF CAB-11
V	8	UHF CAB-4, UHF CAB-5, UHF CAB-10, UHF CAB-17, UHF CAB-19, UHF CMS CAB-20, UHF CMS CAB-22, Pride of India
VI	5	UHF CAB-1, UHF CAB-3, UHF CAB-6, UHF CAB-12, UHF CAB-16

Table 7. Intra (diagonal) and inter cluster ($\sqrt{D^2}$) values among 23 genotypes of cabbage

	I	II	III	IV	V	VI
I	26.50					
II	24.97	14.44				
III	30.38	17.33	22.67			
IV	27.50	11.72	13.02	16.77		
V	15.50	19.59	26.14	22.72	17.99	
VI	21.11	13.56	21.91	17.66	14.34	14.42

Table 8. Intra cluster group means for various components of net head weight in cabbage

Sl. No.	Characters	Cluster means					
		I	II	III	IV	V	VI
1.	Plant height (cm)	35.38	27.4	23.96	24.53	34.10	22.03
2.	Days to 50 % marketable maturity	76.33	74.33	85.67	84.33	74.33	79.33
3.	Non-wrapper leaves	13.56	13.90	12.56	15.45	11.11	10.78
4.	Stalk length (cm)	1.87	4.11	2.81	1.62	1.35	2.93
5.	Equatorial diameter of head	11.85	11.69	10.11	12.87	10.94	12.32
6.	Polar diameter of head	11.89	10.11	9.25	10.09	10.36	11.99
7.	Head shape index	1.04	0.92	0.91	0.76	0.97	0.99
8.	Head compactness	44.96	38.94	59.34	34.79	62.27	30.43
9.	Gross head weight (g)	1796.67	1188.33	916.67	1056.00	1566.67	1430.00
10.	Net head weight (g)	771.67	601.67	493.33	493.33	738.33	543.33
11.	Core length (cm)	7.17	4.67	4.93	6.83	1.07	6.21
12.	Total soluble solids (°Brix)	6.00	6.60	4.70	5.70	6.27	4.87
13.	Ascorbic acid content (mg 100 g^{-1})	10.36	14.83	8.01	10.44	11.82	11.40

Morphological characters

Head shape index determines the shape of head. Based on shape index, 23 genotypes were classified into 2 groups i.e., round (0.8–1) and conical (> 1.0). Maximum number of genotypes produced round (21) shaped head and conical (2) as listed in Table 9. Based on visual observations at marketable harvest, majority of the genotypes were light green (7) or green (13) coloured. Rests of the genotypes were dark green as listed in Table 10 (3).

Table 9. Categorisation of cabbage genotypes based on shape of head

Round (21)	Conical (2)
UHF CAB-1,UHF CAB-2 UHF CAB-3,UHF CAB-4,UHF CAB-5, UHF CAB-6, UHF CAB-8, UHF CAB-9, UHF CAB-10 UHF CAB-11 UHF CAB-12, UHF CAB-13, UHF CAB-14, UHF CAB-15, UHF CAB-17, UHF CAB-19, UHF CMS CAB-20, UHF CMS CAB-22, Pride of India (check) UHF CAB-16 , UHF CAB-7	UHF CAB-18, UHF CMS CAB-21

Table 10. Categorisation of cabbage genotypes based on head colour

Light green (7)	Green (13)	Dark green (3)
UHF CAB-1, UHF CAB-2, UHF CAB-8, UHF CAB-9, UHF CAB-13, UHF CAB-14, Pride of India (check)	UHF CAB-4, UHF CAB-5, UHF CAB-6, UHF CAB-7, UHF CAB-10, UHF CAB-11, UHF CAB-15, UHF CAB-16, UHF CAB-18, UHF CAB-19, UHF CMSCAB-20, UHF CMS CAB-21, UHF CMS CAB-22	UHF CAB-1, UHF CAB-3, UHF CAB-12

Conclusion

Net head weight showed strong and significant associations at both genotypic and phenotypic levels with gross head weight, plant height, head size parameters, head shape index, total soluble solids and ascorbic acid content, highlighting their relevance in cabbage yield improvement. Path analysis indicated that gross head weight and plant height exerted the greatest direct influence on net head weight phenotypically, while gross head weight, plant height and polar head diameter were the major contributors at the genotypic level, supporting their use as reliable selection criteria. Genetic divergence analysis revealed wide variability among the genotypes, with clusters II and III displaying maximum divergence, as confirmed by D^2 statistics. Crossing genotypes from these divergent clusters is expected to enhance heterosis and generate superior segregants. Future breeding programs may capitalise on these findings by combining divergent parents and key yield-determining traits, followed by multi-environment evaluation and molecular-assisted selection to accelerate the development of high-yielding cabbage cultivars.

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Authors' contributions

SK[1] and PS performed the experiment. SK[2] designed the research. PS, AP, SK[1] wrote the manuscript. CY, SK, AK and HT revised and corrected the manuscript. All authors have contributed for different sections of writing, reviewing, correction and statistical analysis. All authors have read and approved the final manuscript [SK[1]- Sandhya Kumari; SK[2]- Shorya Kapoor].

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