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MORPHOPHYSIOLOGICAL AND BIOCHEMICAL CHARACTERIZATION OF THE EXOTIC CABBAGE (*BRASSICA OLERACEA* VAR. *CAPITATA* L.) VARIETIES IN BANGLADESH

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SUMMARY

Evaluation of nine exotic cabbage varieties and a local variety commenced at the Research Field of the Department of Agriculture, Noakhali Science and Technology University (NSTU), Bangladesh, following a randomized complete block design (RCBD) with three replications. This study aimed to identify the most suitable exotic varieties based on morphophysiological and biochemical traits compared with a check variety. Significant variations ($P < 0.01$) for all the characteristics, except chlorophyll content, emerged from the study. A highly significant positive association ($r \geq 0.75$) was evident for the head diameter of cabbage varieties with head width, stump thickness, core length, and weight with folded and unfolded leaves. On cluster analysis, varieties V2, V3, and V10 were in the same clusters. About the PCA, PC1 accounted for 50.29% of the total variation. However, the maximum plant diameter (65 cm) occurred in V10, and the widest leaf petiole length (8.13 cm) was visible in V3. Yet, the highest head length (13.16 cm), head diameter (19.51 cm), head width (18.33 cm), weight with unfolded leaves (2.00 kg), and weight with folded leaves (1.44 kg) appeared in V10, which are very close to V2 and V3. Also, genetic parameters estimation and heatmap analysis revealed high genetic advance and positive variation, respectively, regarding head diameter, head width, and weight with folded and unfolded leaves. Finally, V2 and V3 varieties could better serve for further genetic improvement for cabbage growers and plant breeders in Bangladesh.

Keywords: biochemical, cabbage, genetic advance, morphophysiological, varietal improvement

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Key findings: Varieties V2 and V3 exposed substantial positive results regarding head diameter, width, and length, cabbage weight with folded and unfolded leaves, TSS, and vitamin C compared with the check variety. Further molecular study should continue with these two varieties against each trait for future breeding programs.

INTRODUCTION

The vegetable known as cabbage (*Brassica oleracea* L. var. *capitata,* [2n = 18]) is widely grown all over the world, having started in the Mediterranean and moving up to the North Sea (Li *et al.*, 2021). Before cultivation and use as food, cabbage was mainly beneficial for medicinal purposes (Silva Jr, 1986). It is rich in health-promoting phytochemicals, i.e., glucosinolates, phenolics, especially flavanols and phenolic acids, vitamins, and carotenoids, which all together contribute to the immense significance of this genus in the human diet (Francisco *et al.*, 2017). Cabbage is vital in agriculture and horticulture, contributing both to the economy and health of populations worldwide. Total production of cabbage with other brassica reached 72,604 kt globally (FAOSTAT 2022). The world exports of cabbages, cauliflowers, kohlrabi, kale, and similar edible brassicas, fresh or chilled, exceeded USD3.72 billion (according to external trade statistics of 85 countries).

There are over 400 different varieties of cabbage grown throughout the globe, from round to conical in shape, with flat or curly, tight or loose leaves, and in green, white, red, and purple colors. Cabbage cultivation is mainly for its head, which consists of water (92.8%), protein (1.4 mg), calcium (55.0 mg), and iron (0.8 mg), with the leaves eaten raw in salads or cooked (Teshome and Bobo, 2018). The optimum mean temperature for growth and quality head development is 15 °C–18 °C, with a minimum temperature of 4 °C and a maximum of 24 °C. Cabbage grows well on the spread of soils with adequate moisture and fertility. It tolerates a soil pH range of 5.5–6.8, and it is a significant feeder. Cabbage is a vital and nutritious winter vegetable in Bangladesh. It contains a range of essential vitamins and minerals, a bit of protein, and good caloric value. However, in the growing season of 2021–2022, cabbage production accounted for 0.395 million tons in Bangladesh, which is quite a low proportion of worldwide cabbage production (BBS, 2022).

Cultivar selection is one of the most crucial decisions a commercial grower must make each season. Variety selection is a dynamic process. After a few growing seasons, newer cultivars may replace those varieties that have been profitable for years. It intensely increases crop productivity in addition to cultivars. Based on Janko *et al.* (2011), breeding cabbage varieties have generated good-producing mature heads relatively early in the growing season. Their study revealed head shape, size, and density correlating with the earliest head formation to meet market demands (Kenneth, 2012). Contrastingly, it is rich in essential vitamins, minerals, and amino acids. Thus, to fulfill the population's nutritional demands, more cabbage output can boost the country's economy. Increasing the yield of vegetable crops can help the nation's economy and meet its dietary needs. With the introduction of the most acceptable cultivars from overseas, there is a significant opportunity to increase cabbage production. Therefore, varietal evaluation should proceed before suggesting to farmers what cabbage varieties are best for cultivation. Hence, the experiment ensued to introduce some exotic cabbage varieties for better yield performance in Bangladeshi environmental conditions.

MATERIALS AND METHODS

Experimental site and planting materials

The study commenced at the Research Field of the Department of Agriculture, Noakhali Science and Technology University (NSTU), Sonapur, Noakhali, from October 2020 to March 2021. The location of the research field

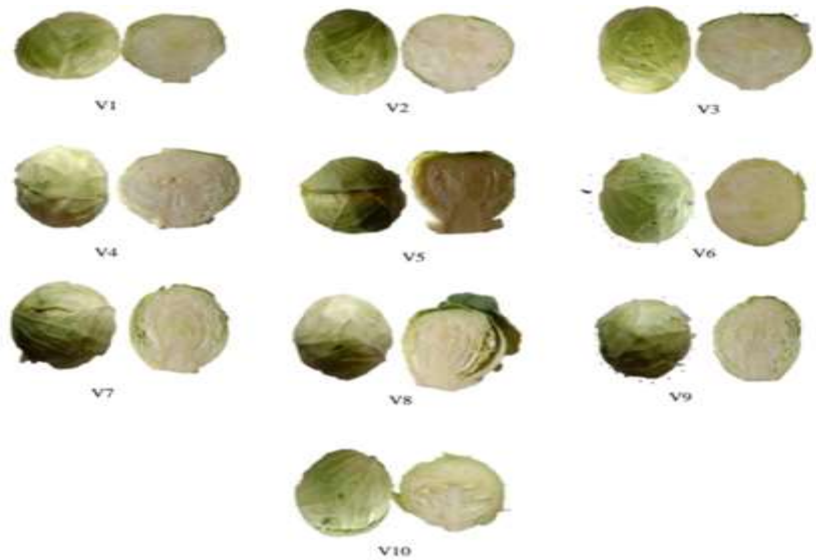

Figure 1. Morphological distribution of 10 cabbage varieties where V1 to V9 = Exotic and V10 = Provati (Check variety).

is 2200′ N to 23010′ N latitude and 89050′ E to 91030′ E longitude, and the soil type is sandy loam.

Nine cabbage varieties for evaluation came from the Department of Agriculture, Noakhali Science and Technology University, and a high-yielding commercial cabbage variety (Provati), developed by the Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur, served as a check variety (Figure 1).

Land preparation

The experimental plots bore plowing, harrowing, and leveling. Removing all types of weeds and debris from the previous crop ensued, and the land's final preparation included the addition of a basal dose of cow dung. Recommended fertilizer doses of cow dung were 10–15 t/ha (N100, P100, and K80 kg/ha), S at 60 kg/ha, and B at 8 kg/ha. Applying the total amount of cow dung, P in the form of triple superphosphate (TSP), 1/3 of N, ½ of MOP, 1/3 of gypsum, and Borax happened at the time of final land preparation before laying the black plastic mulch on the bed.

Design and layout of the experiment

The 28-day-old seedlings transplanting in the main field followed a randomized complete block design (RCBD) with three replications. Each replication contains 10 plots of 1.8 m × 1 m size, giving 30-unit plots.

Data collection

Morphophysiological traits

Data recording on morphophysiological traits included plant height and diameter (cm), leaf petiole length and width (cm), number of unfolded and folded leaves, number of total leaves, head length, diameter, and width (cm), stump length and thickness (cm), core length and width (cm), weight with folded and unfolded leaves (kg), number of root per plant, root length (cm), and head firmness (kg/cm2). Data collection for each plot incurred averaging the performance of five individuals present in each plot.

Biochemical traits

The leaf chlorophyll content measurement used a hand-held SPAD-502 Plus chlorophyll content meter (Konica Minolta, Japan), with a Leather and Paper pH Portable Meter HI99171 by Hanna Company used for fruit pH measurement (Danner *et al.,* 2015). Inversely, the oxidation-reduction titration method helped determine vitamin C levels, and measuring the TSS of selected varieties employed an Atago 3810 (PAL-1) digital pocket refractometer, 0–53% Brix.

Statistical analysis

The data illustration as a mean ± standard deviation and attaining one-way analysis of variance (ANOVA) was at a significant level, $p \leq 0.05$ with RCBD. Computing the ANOVA of the different morphophysiological and biochemical traits, Tukey's pairwise comparison, correlation coefficient, and multivariate analysis, i.e., Principal Component Analysis (PCA) and cluster analysis ran the Minitab 19 statistical software package (Minitab Inc., State College, PA, USA). Genetic advances in the percent of mean calculation employed the formula of Comstock and Robinson (1952). The cluster heatmap generation utilized the ClustVis online software (Metsalu and Vilo, 2015).

RESULTS AND DISCUSSION

Variations of morphophysiological and biochemical traits

The leaves, tightly arranged, formed a headed cabbage and a definite shape, with folded leaves, average size, and better appearance varieties (V2 and V3) that are options for future analysis. For all the characteristics, except chlorophyll content, significant variations ($P < 0.01$) were noteworthy in the study. There is a clear morphological visualization of 10 cabbage varieties (Figure 1). In this study, the highest plant height (29.5 cm) was visible in V4, followed by the check variety V10, and the shortest plant height (24.9 cm) occurred in V5, followed by V2 (Table 1). Eva *et al.* (2020) also reported a similar range of cabbage plant height in Bangladesh. The highest plant diameter (65 cm) was evident in the check variety V10, followed by the varieties, V3 and V2, while the lowest plant diameter (45.3 cm) appeared in V1.

The number of unfolded leaves is also an influential morphological trait because it is the chief photosynthetic part of cabbage. In this study, the number of unfolded leaves ranged from 14 to 23, where V6 and V10 attained the maximum and minimum numbers, respectively. The number of folded leaves is vital in the cabbage plants' head weight trait consideration. Here, counting the number of folded leaves (18–26) provided the maximum number of folded leaves in the V10 variety, and the minimum number was in the V8 variety, which agrees with the result of Moniruzzaman (2011). The total number of leaves (49) was highest in the V4 variety, which was statistically significant from all other varieties, and the lowest number of leaves (38) came from the V8 variety. Hasan and Solaiman (2012) also found the same range of total number of leaves in cabbage.

Similarly, head length is a primary yield-contributing trait in cabbage. The maximum head length (13.1 cm) emerged in the V10 check variety, followed by the V8 variety. The minimum head length (6.5 cm) was evident in V6, followed by the V5 variety (Table 1). Similar findings also resulted from the study of Kibar *et al.* (2015). However, the highest head diameter (19.5 cm) surfaced from the V10 check variety, and the lowest head diameter (7.7 cm) was apparent in the V6 variety. Teshome and Bobo (2019) also recorded similar observations of head diameter.

The presented study measured the maximum head width (18.4 cm) in check variety V10, followed by varieties V3 and V2, and the minimum head width (6.2 cm) resulted in the V6 variety, followed by the V4 variety (Table 1). Analogous findings came from the research by Bhandari *et al.* (2021). Moreover, the cabbage leaf petiole length and width are crucial parameters because they are essential

Table 1. Performance of morphophysiological traits of 10 cabbage varieties.

Varieties	PH (cm)	PD (cm)	LPL (cm)	LPW (cm)	NUL	NFL	NL	HL (cm)	HD (cm)	HW (cm)	HF (kg/cm^{2})	SL (cm)	ST (cm)	CL (cm)	CW (cm)	WWFL (kg)	WWUL (kg)	NR	RL (cm)
V1	25.2^{c}	45.3^{a}	6.1^{bc}	1.1^{c}	17^{cd}	23^{ab}	48^{ab}	10.7^{bc}	12.3^{c}	11.5^{d}	5.1^{bc}	7.8^{cd}	1.6^{b-d}	1.6^{b-d}	2.7^{bcd}	0.6^{cd}	1.3^{c}	18.3^{ab}	21^{a-c}
V2	25.0^{c}	57.3^{ab}	5.2^{b-d}	1.3^{ab}	18^{cd}	22^{c}	44^{a-c}	10.6^{bc}	14.7^{b}	13.9^{bc}	5.9^{ab}	9.2^{bc}	1.7^{bc}	1.7^{de}	3.1^{a-c}	1.0^{b}	1.7^{b}	19^{ab}	19^{c}
V3	26.4^{bc}	60.6^{a-c}	8.1^{a}	1.8^{a}	20^{bc}	22^{cd}	45^{a-c}	11.2^{ab}	14.8^{b}	14.7^{b}	5.4^{b}	10.1^{ab}	1.7^{bc}	1.7^{bc}	3.4^{a}	1.1^{b}	1.8^{ab}	19.3^{ab}	21.6^{a-c}
V4	29.5^{a}	57.3^{a-c}	5.1^{b-d}	1.5^{a-c}	22^{ab}	23^{bc}	49^{a}	8.5^{cd}	7.8^{e}	6.9^{fg}	6.9^{a}	10.2^{ab}	1.5^{b-d}	1.5^{ef}	2.7^{b-d}	0.4^{de}	0.9^{d}	18.6^{ab}	19.7^{bc}
V5	24.9^{c}	50.0^{a-c}	5.9^{b-d}	0.9^{c}	21^{a-c}	21^{cd}	43^{a-c}	7.6^{d}	10.5^{cd}	10.2^{de}	4.8^{bc}	6.5^{d}	1.7^{bc}	1.7^{c-e}	2.5^{c-e}	0.4^{e}	0.8^{d}	21^{a}	19.7^{bc}
V6	27.1^{a-c}	56.7^{b-d}	4.8^{cd}	1.9a	23^{a}	24^{cd}	48^{ab}	6.5^{d}	7.7^{e}	6.2^{g}	4.8^{bc}	8.3^{c}	1.6^{bc}	1.6^{f}	2.1^{de}	0.3^{e}	0.9^{d}	18.3^{ab}	20^{bc}
V7	25.9^{c}	48.3^{cd}	6.2^{b}	1.0^{c}	21^{ab}	22^{cd}	44^{a-c}	10.0^{bc}	9.1^{dc}	8.8^{ef}	3.7^{c}	8.6^{bc}	1.4^{cd}	1.5^{de}	2.6^{b-e}	0.4^{e}	0.8^{d}	19.6^{ab}	21.5^{a-c}
V8	26.7^{a-c}	53.3^{cd}	4.7^{d}	1.2^{bc}	15^{d}	18^{cd}	38^{d}	12.0^{ab}	12.1^{c}	11.7^{cd}	4.6^{bc}	11.2^{a}	1.7^{b}	1.7^{b}	3.3^{ab}	0.8^{c}	1.2^{c}	16^{b}	25^{a}
V9	25.6^{c}	46.2^{a}	5.1^{b-d}	1.2^{bc}	19^{bc}	20^{d}	41^{cd}	8.4^{cd}	8.1^{e}	8.4^{e-g}	4.6^{bc}	8.3^{c}	1.4^{d}	1.4^{ef}	2.0^{e}	0.3^{e}	0.5^{e}	20^{ab}	21.4^{a-c}
V10	28.8^{ab}	65.0^{d}	5.0^{b-d}	1.7^{ab}	14^{e}	26^{a}	43^{b-d}	13.1^{a}	19.5^{a}	18.4^{a}	4.9^{bc}	8.9^{bc}	2.0^{a}	2.0^{a}	3.2^{ab}	1.4^{a}	2.0^{a}	21.6^{a}	23.6^{ab}
P value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	>.05	<.001	<.001	<.001	<.001	<.001
CV (%)	3.48	5.70	8.13	15.25	6.15	23.34	3.34	6.98	6.48	7.66	7.57	5.28	3.82	4.16	7.02	13.36	7.13	7.80	6.55

Means in columns followed by the same letter are not significantly different at p = 0.05, PH- Plant height, PD- Plant diameter, LPL- Leaf petiole length, LPW- Leaf petiole width, NUL- No. of unfolded leaves, NFL- No. of folded leaves, NL- No. of total leaves, HL- Head length, HD- diameter, HW- Head width, HF- Head firmness, SL- Stump length, ST- Stump thickness, CL- Core length, CW- Core width, WWFL- Weight with folded leaves, WWUL- Weight with unfolded leaves, NR- No. of root per plant, RL- Root length.

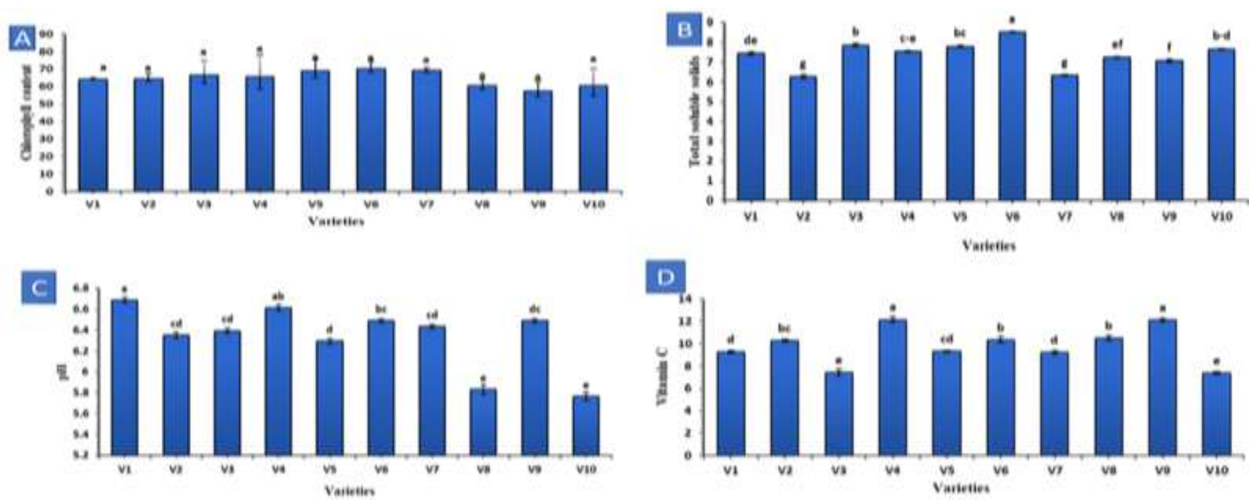

Figure 2. Biochemical analysis: A) chlorophyll content, B) total soluble solids, C) pH, and D) vitamin C of 10 cabbage varieties where V1 to V9 = Exotic and V10 = Provati (Check variety).

in leaf shape formation. Leaf petiole length of 4.7–8.1 cm and leaf petiole width of 0.9–1.9 cm were notable in the study. The parallel range of leaf petiole width was a finding from Sun *et al.* (2021).

Head firmness is a valuable physiological trait of cabbage since cabbage's degrees of head solidity depend on it. This research obtained the maximum head firmness (6.9 kg/cm^2) in the V4 variety, which was significantly different from the other varieties, followed by the variety V2 (5.9 kg/cm^2), with the minimum head firmness (3.7 kg/cm^2) recorded in the V7 variety. Also, the cabbage stump length (6.5–11.2 cm) observation is made available in Table 1. The said range of stump length is also shown in past studies (Kaminski, 2010). The stump thickness of cabbage resulted in the range of 1.4 to 2.0 cm, as recorded by Sarkar and Rahman (2021). This experiment estimated core length at 1.4–2.0 cm and width at 2.0–3.4 cm.

The most prominent morphological trait is the head weight with folded leaves because it directly relates to cabbage's yield performance, and a significant variation among the varieties occurred regarding the trait head weight with folded leaves. The varieties V2 and V3 performed better than the check variety (V10) regarding plant diameter, weight with folded leaves, and head width than any other traits studied in the varieties. However, for weight with folded leaves, the maximum weight (1.4 kg) appeared in the V10 check variety, followed by the V3 and V2 varieties, with the lowest weight with folded leaves (0.3 kg) observed in the V6 and V9 varieties (Table 1). Comparably, the weight with unfolded leaves (0.5–2.0 kg) obtained in this study shares these result types found by Teshome and Amide (2020). Cabbage root length plays a vital role in the uptake of water and nutrients, and the cabbage root length ranged from 19 to 25 cm, as revealed in this study, which aligned with Hasan and Solaiman (2012).

Among the biochemical traits, the maximum chlorophyll content (70.4) (SPAD value) resulted in V6 and the minimum (57.56) (SPAD value) in V9 (Figure 2A), with similar findings recorded by Chatterjee (2010). The maximum vitamin C (12.16 mg/100 g) appeared in the V4 variety, followed by the V9 variety (12.13 mg/100 g), while the minimum vitamin C (7.33 mg/100 g) evident in the V10 variety, followed by V3 (7.44 mg/100 g) (Figure 2D). The same observations came from Adelanwa and Medugu (2015). Also, the studied pH of cabbage showed a range of 5.69 to 6.72 (Figure 2C). Additionally, the cabbage's total soluble solids (TSS) are an effective biochemical trait based on human nutrition. Notably, a significant TSS (6.1–8.6 Brix%) emerged in this study (Figure 2B), which is relevant in determining the quality of produce, and a similar result occurred in the past (Singh and Vidyasagar, 2012; Saha *et al*., 2015; Thakur *et al*., 2015; Bhat *et al.,* 2017).

Genetic parameters estimation

Genetic diversity and variability are vital in selecting a variety for a successful breeding program. It is a helpful and essential tool for choosing parents in hybridization to develop high-yield potential varieties to meet the diversified goals of plant breeding (Arslanoglu *et al*., 2011). High heritability combined with robust genetic gain has proven preferable to high heritability alone for choosing suitable varieties for earliness and high yield (Khan *et al*., 2013). In this study, almost all the variables showed high heritability, except chlorophyll content, followed by the number of roots, with a difference between GCV and PCV of more than 20% (Table 2). Özer *et al.* (2023) recorded high heritability for cabbage head length (91.56%), core length (91.38%), head diameter (82.24%), and head weight (81.86%).

All other variables, however, revealed minor differences between GCV and PCV. Cabbage weight with folded leaves (135.41%), weight with unfolded leaves (106.15%), head width (84.53%), head diameter (80.15%), and core length (70.03%) accounted for high genetic advances. Meanwhile, leaf petiole width (50.32%), head length (49.65%), number of unfolded leaves (47.47%), leaf petiole length (42.22%), number of folded leaves (39.17%), core width (38.77%), head firmness (36.70%), and stump length (34.77%) recorded a

Table 2. Genetic parameters estimation of the traits studied in the cabbage varieties.

Traits	σ^2g	σ^2P	GCV	PCV	h^2b	GA (5%)	GA% (mean)
PH	3.27	4.19	6.81	7.71	78.02	3.29	12.40
PD	58.0	68.6	14.1	15.33	84.56	14.43	26.71
LPL	1.51	1.71	21.8	23.21	88.31	2.38	42.22
LPW	0.15	0.19	27.59	31.17	78.38	0.69	50.32
NUL	19.80	21.27	23.88	24.75	93.10	8.84	47.47
NFL	18.39	20.68	20.16	21.38	88.93	8.33	39.17
CLC	9.54	44.25	4.77	10.26	21.56	2.95	4.56
NL	16.61	20.06	9.12	10.03	82.80	7.64	17.10
HL	6.26	6.92	25.34	26.64	90.46	4.90	49.65
HD	21.15	21.68	39.39	39.88	97.56	9.36	80.15
HW	21.37	22.02	41.65	42.28	97.05	9.38	84.53
HF	1.02	1.26	19.80	22.01	80.95	1.87	36.70
SL	2.59	2.95	18.02	19.23	87.78	3.10	34.77
ST	0.05	0.06	12.92	14.28	81.82	0.40	24.07
CL	2.67	2.73	34.38	34.76	97.80	3.33	70.03
CW	0.32	0.37	20.26	21.81	86.30	1.07	38.77
WWFL	0.22	0.23	67.25	68.79	95.56	0.93	135.41
WWUL	0.39	0.39	51.53	51.53	100.0	1.29	106.15
NR	2.58	4.84	8.37	11.46	53.31	2.42	12.58
RL	3.99	6.50	9.39	11.98	61.38	3.22	15.15
pH	0.14	0.14	5.90	5.96	97.89	0.76	12.02
TSS	0.72	0.73	11.47	11.55	98.62	1.73	23.46
VIT C	4.00	4.11	20.37	20.65	97.32	4.06	41.40

σ^2g = Genotypic variance, σ^2P = Phenotypic variance, GCV = Genotypic co-efficient of variation, PCV = Phenotypic co-efficient of variation, h^2b = Heritability, GA = Genetic advance, GA (%) = Genetic advance in the percentage of the mean. PH- Plant height, PD- Plant diameter, LPL- Leaf petiole length, LPW- Leaf petiole width, NUL- No. of unfolded leaves, NFL- No. of folded leaves, NL- No. of total leaves, CLC- Chlorophyll content, HL- Head length, HD- Head diameter, HW- Head width, HF- Head firmness, SL- Stump length, ST-Stump thickness, CL- Core length, CW- Core width, WWFL- Weight with folded leaves, WWUL- Weight with unfolded leaves, NR- No. of root per plant, RL- Root length, TSS- Total soluble solids, VIT C- Vitamin C.

comparatively moderate genetic advance of the mean (Table 2). Plant diameter (14.43%), head diameter (9.36%), and head width (9.38%) possessed high genetic advances, while weight with unfolded leaves (1.29%) showed moderate genetic advance, together with the GCV and PCV value (51.53). Özer *et al.* (2023) reported the highest genetic advance as a percent of the mean for head volume (35.0%), followed by core length (29.52%) and head density (27.09%).

Correlation analysis among the morphophysiological and biochemical traits

The presence of significant correlations among traits and their assessment would facilitate an advanced procedure of indirect selection aimed at improving a character by selecting it over another (Sorkheh *et al.*, 2010). A close relationship between traits could facilitate or hinder the breeding process since selecting a given trait could favor the presence of another desirable or undesirable trait. This research found high positive correlations (0.967) between weight with folded leaves and head diameter (Table 3). A highly significant positive association ($r \geq 0.75$) was evident for the head diameter of cabbage varieties with head width, stump thickness, core length, and weight with folded and unfolded leaves (Table 3). Positive correlations were also manifesting between head length and head diameter (0.831) in the presented study, agreeing with a high correlation between head length and head diameter, as observed in cabbage by Cervenski *et al.* (2012).

Table 3. Estimation of Pearson's correlation coefficients among different morphphysiological and biochemical traits of cabbage varieties.

Traits	PH	PD	LPL	LPW	NUL	NFL	CLC	NL	HL	HD	HW	HF	SL	ST	CL	CW	WWFL	WWUL	NR	RL	pH	TSS	VIT. C
PH	1																						
PD	0.65	1																					
LPL	-0.28	0.01	1																				
LPW	0.63	0.80	0.07	1																			
NUL	-0.17	-0.34	0.20	-0.06	1																		
NFL	-0.14	-0.19	0.36	0.12	0.83	1																	
CLC	-0.09	0.01	0.35	0.08	0.70	0.75	1																
NL	0.22	0.08	0.25	0.34	0.49	0.83	0.60	1															
HL	0.13	0.37	0.17	0.08	-0.84	-0.59	-0.50	-0.38	1														
HD	0.10	0.60	0.20	0.30	0.82	-0.51	-0.31	-0.20	0.83	1													
HW	0.03	0.54	0.25	0.23	-0.82	-0.55	-0.37	-0.29	0.85	0.99	1												
HF	0.43	0.41	-0.03	0.30	0.09	0.25	-0.01	0.45	-0.06	0.05	0.01	1											
SL	0.49	0.45	-0.03	0.35	-0.24	-0.23	-0.32	-0.24	0.49	0.17	0.18	0.35	1										
ST	0.31	0.70	0.70	0.40	-0.74	-0.55	-0.15	-0.18	0.57	0.84	0.79	-0.01	.06	1									
CL	0.31	0.50	0.03	0.24	-0.89	-0.70	-0.42	-0.30	0.82	0.87	0.80	-0.15	0.15	0.84	1								
CW	0.17	0.58	0.35	0.22	-0.58	-0.35	-0.15	-0.21	0.88	0.77	0.78	0.26	0.61	0.57	0.62	1							
WWFL	0.26	0.74	0.17	0.46	-0.78	-0.47	-0.37	-0.17	0.83	0.96	0.95	0.18	0.38	0.81	0.83	0.83	1						
WWUL	0.15	0.70	0.30	0.48	-0.66	-0.26	-0.17	-0.03	0.78	0.93	0.91	0.22	0.35	0.75	0.73	0.85	0.96	1					
NR	0.02	0.18	0.20	0.06	-0.13	-0.13	0.03	0.09	0.03	0.30	0.31	-0.12	-0.59	0.29	0.35	-0.14	0.18	0.09	1				
RL	0.24	0.14	-0.11	0.06	-0.67	-0.76	-0.56	-0.65	0.68	0.40	0.43	-0.44	0.49	0.41	0.66	0.45	0.42	0.29	-0.22	1			
pH	-0.26	-0.49	0.29	-0.13	0.76	0.87	0.41	0.71	0.63	-0.62	-0.63	0.27	-0.32	-0.78	-0.76	-0.54	0.63	-0.46	-0.06	-0.75	1		
TSS	0.37	0.31	.004	0.58	0.15	0.15	0.24	0.33	0-.33	-0.06	-0.12	0.12	-0.13	0.27	0.04	-0.16	-0.03	0.01	0.03	0.02	-0.02	1	
VIT C	0.03	-0.42	-0.58	-0.29	0.41	0.14	-0.20	-0.03	0-.56	-0.74	-0.75	0.29	0.10	-0.66	-0.70	-0.58	-0.65	-0.71	-0.39	-0.31	0.39	-0.18	1

Red, Blue, and Black colors narrate 1% level of significance, 5% level of significance, and non-significance, respectively. Legends: PL- Plant length, PD- Plant diameter, LPL- Leaf petiole length, LPW- Leaf petiole width, NUL- No. of unfolded leaves, NFL- No. of folded leaves, NL- No. of total leaves, CLC- Chlorophyll content, HL- Head length, HD- Head diameter, HW- Head width, HF- Head firmness, SL- Stump length, ST- Stump thickness, CL- Core length, CW- Core width, WWFL- Weight with folded leaves, WWUL- Weight with unfolded leaves, NR- No. of root per plant, RL- Root length, TSS- Total soluble solids, VIT C- Vitamin C.

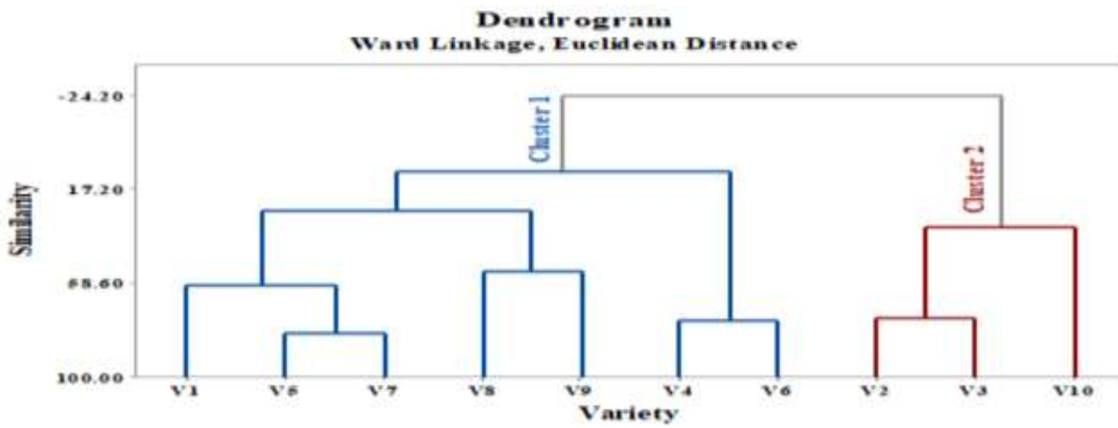

Figure 3. Dendrogram for cluster analysis of 10 cabbage variety based on morphphysiological and biochemical traits.

Cluster analysis

The cluster analysis grouped the 10 cabbage varieties into two prime clusters based on cabbage morphophysiological and biochemical traits. The varieties with similar features incur placement in the same cluster following the Euclidean distance dendrogram. The clustering diagram of all cabbage varieties is available in Figure 3. In this study, cluster 1 comprises seven varieties (70%), including V1, V4, V5, V6, V7, V8, and V9; cluster 2 contained three varieties (30%) in the dendrogram, including V2, V3, and V10. The dendrogram also showed that cluster 1 classifies into two primary subgroups regarding their similarity index. The varieties V2 and V3 bore plotting in the same cluster with the check variety, hence, their reason for selection. Also, morphological and chemical characteristics of 15 distinct genotypes of *Brassica napus* were notable through cluster analysis, and the genotypes varied significantly, dividing the genotypes into five clusters, with clusters 2 and 3 having the least diversity and clusters 1, 4, and 5 having the most (Tariq *et al.* 2020).

Principal component analysis (PCA)

PCA is beneficial as it gives information about the groups where certain traits are more critical, allowing the breeders to conduct specific breeding programs (Yousuf *et al.*, 2011). PCA proved effective for getting the variations of the total data like head diameter, head width, and weight with folded and unfolded leaves, as well as for vitamin C in the V2 and V3. The maximum 15 traits identified that contributed positively in PC1 included plant height and diameter, leaf petiole length and width, head length and width, head diameter, stump length and thickness, core length and width, weight with folded and unfolded leaves, number of roots, and root length (Table 4). However, the rest of the eight traits, such as the number of folded and unfolded leaves, chlorophyll content, total leaves, head firmness, pH, total soluble solids, and vitamin C, gave negative contributions. The PC2 accounted for 19.27% of the total variation, mainly attributed to plant diameter, leaf petiole width, number of folded leaves, chlorophyll content, total leaves, head length, and core length (Table 4). The PC3 accounted for 13.67% of the total variation, linked with plant diameter, leaf petiole width, stump length, and vitamin C (Table 4). In this study, the first three components, 50.29%, 19.27%, and 13.67%, showed most of the variations, respectively, and wholly explained 83.23% of the total variation, aligning with the results of Kibar *et al.* (2016) in different traits. However, considering the PCA of 23 traits of 10 cabbage varieties in this study suggests remarkable variation among the varieties for different morphological traits, especially V2 and V3 (Figures 4a and 4b).

Table 4. Eigen values, proportion of variability, and different traits that contributed to the first five Principal Components (PC) in the cabbage varieties.

Traits	Eigen vectors				
	PC1	PC2	PC3	PC4	PC5
Plant height	0.090	0.177	-0.417	-0.211	0.000
Plant diameter	0.201	0.290	-0.204	-0.102	-0.033
Leaf petiole length	0.019	0.220	0.332	0.301	0.266
Leaf petiole width	0.105	0.345	-0.236	-0.167	0.152
No. of unfolded leaves	-0.277	0.159	0.002	0.055	0.167
No. of folded leaves	-0.217	0.312	0.074	0.175	0.065
Chlorophyll content	-0.141	0.299	0.172	-0.010	0.273
No. of total leaves	-0.124	0.403	0.024	0.012	-0.117
Head length	0.277	-0.077	0.034	0.240	0.013
Head diameter	0.290	0.081	0.144	0.036	-0.140
Head width	0.290	0.042	0.168	0.066	-0.126
Head firmness	-0.004	0.264	-0.298	0.194	-0.453
Stump length	0.124	0.000	-0.420	0.354	0.191
Stump thickness	0.264	0.094	0.034	-0.252	-0.025
Core length	0.288	-0.020	0.083	-0.154	-0.010
Core width	0.251	0.090	-0.018	0.341	0.088
Weight with folded leaves	0.294	0.120	0.017	0.085	-0.112
Weight with unfolded leaves	0.266	0.192	0.061	0.170	-0.065
Number of roots	0.050	0.096	0.321	-0.363	-0.335
Root length	0.205	-0.242	-0.117	-0.039	0.410
pH	-0.252	0.168	0.080	0.190	-0.144
Total soluble solids	-0.008	0.246	-0.120	-0.396	0.327
Vitamin C	-0.202	-0.182	-0.342	0.039	-0.272
Eigen value	10.385	3.980	2.823	2.080	1.380
Variation (%) explained	50.29	19.27	13.67	10.07	6.68

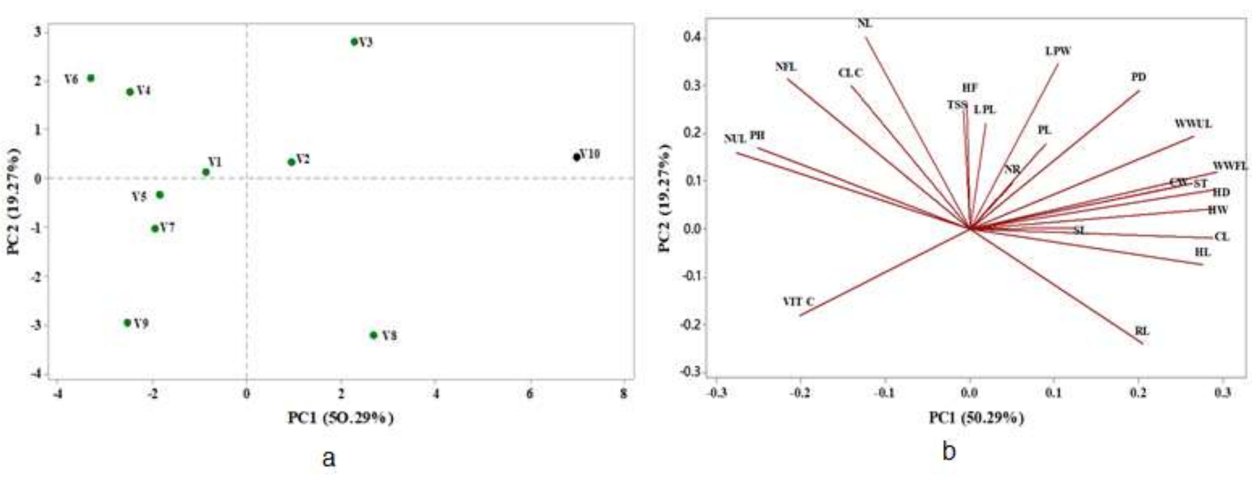

Figure 4. Principal Component Analysis: **a.** Score plot distribution and **b.** Loading plot distribution based on morphophysiological and biochemical traits of 10 cabbage varieties.

PL- Plant length (height), PD- Plant diameter, LPL- Leaf petiole length, LPW- Leaf petiole width, NUL- No. of unfolded leaves, NFL- No. of folded leaves, NL- No. of total leaves, CLC- Chlorophyll content, HL- Head length, HD- Head diameter, HW- Head width, HF- Head firmness, SL- Stump length, ST- Stump thickness, CL- Core length, CW- Core width, WWFL- Weight with folded leaves, WWUL- Weight with unfolded leaves, NR- No. of root per plant, RL- Root length, TSS- Total soluble solids, VIT C- Vitamin C. First principal component (PC1), second principal component (PC2).

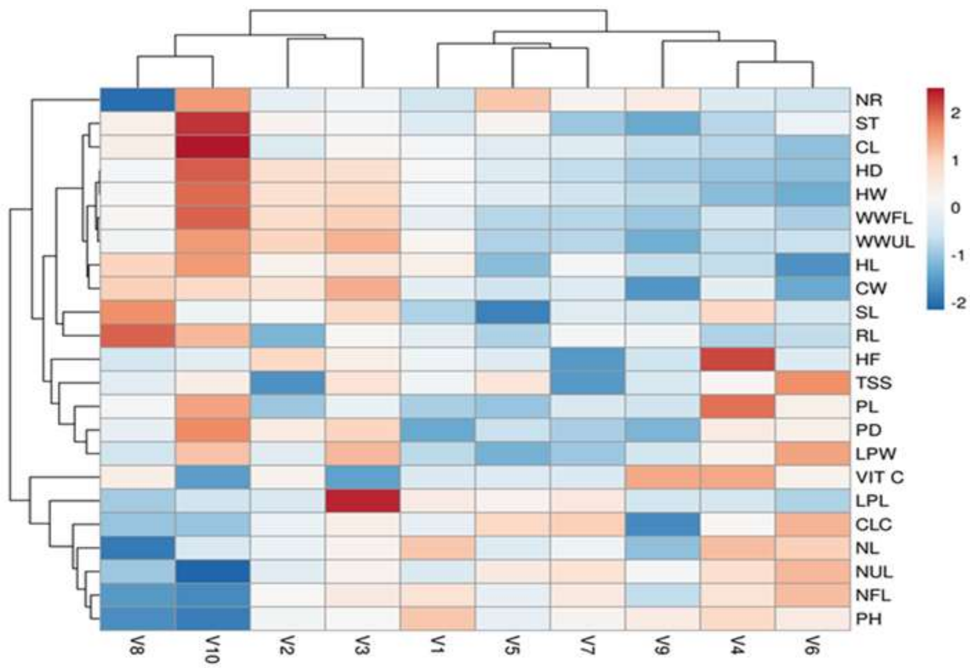

Figure 5. Visualization of the morphophysiological and biochemical traits of cabbage variety based on hierarchical clustering heatmap. The bar at the apex of the heat map (right) represents the relative expression values.

PL- Plant length (height), PD- Plant diameter, LPL- Leaf petiole length, LPW- Leaf petiole width, NUL- No. of unfolded leaves, NFL- No. of folded leaves, NL- No. of total leaves, CLC- Chlorophyll content, HL- Head length, HD- Head diameter, HW- Head width, HF- Head firmness, SL- Stump length, ST- Stump thickness, CL- Core length, CW- Core width, WWFL- Weight with folded leaves, WWUL- Weight with unfolded leaves, NR- No. of root per plant, RL- Root length, TSS- Total soluble solids, VIT C- Vitamin C.

Heatmap analysis based on morphophysiological **and biochemical traits**

Genetic analysis of morphological traits in *Brassica rapa* recombinant inbred line received analysis through a clustered heatmap (Bagheri *et al*., 2012). A total of 23 traits underwent analysis for the cabbage varieties. Figure 5 shows the two-dimensional data visualization approach, i.e., heat map analysis to obtain a detailed overview and better understand the morphophysiological and biochemical traits of the investigated varieties of cabbage, with analysis also done by Yadav *et al.* (2023). The varieties V8, V10, V2, and V3 comprised one of the two major clusters, and the remaining varieties for the second cluster (Figure 5). The first cluster's primary identification came from favorable significant variations in the head diameter, head width, weight with folded and unfolded leaves, and core width (Figure 5). Plant length, plant diameter, leaf petiole width, and weight with folded and unfolded leaves all exhibited negative variation in the second cluster's first chief sub-cluster (V1, V5, and V7), and pH accounted for a moderately positive variation. Gao *et al.* (2021) carried out a heat map analysis to determine the effect of low light intensity on broccoli microgreen growth and phytochemicals, and the study revealed from measured parameter responses, the 30 and the 50 $\mu mol.m^{-2}.s^{-1}$ clusters are the closest to each other, while the 70 and the 90 $\mu mol.m^{-2}.s^{-1}$ clusters are the closest to each other.

CONCLUSIONS

Among the varieties, the performance of V2 and V3 varieties could be options for future breeding programs compared with the check variety based on morphophysiological and biochemical traits. They were comparatively superior for head diameter, head width, and weight with folded and unfolded leaves, as well as for vitamin C. Also, all these traits contributed positively in PC1 and PC2, exhibiting a significant genetic advance based on different genetic parameter estimations, as these traits also showed a positive interaction in the heatmap analysis. Additionally, these two varieties also incurred placement in the same sub-cluster of the Euclidean dendrogram. On the whole analysis, these two varieties are promising in Bangladeshi climatic conditions. Therefore, V2 and V3 varieties could undergo further study at the molecular levels in the future crop improvement program.

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