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Comparative Evaluation of Agronomic Performance and Morphological Variation of Local and Commercial Cabbage (*Brassica oleracea* var. *capitata* L.) Genotypes under High-Altitude Conditions of Van, Türkiye

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ABSTRACT

This study aimed to evaluate the agronomic performance and morphological variation of local and commercial cabbage genotypes under high-altitude conditions in Van, Türkiye. The research was conducted over two growing seasons (2024–2025). In the first year, 35 local cabbage genotypes were subjected to pre-selection using a multi-criteria evaluation approach, and 20 superior genotypes were selected. In the second year, these genotypes, together with five commercial cultivars, were evaluated under field conditions using a randomized complete block design with three replications. Significant differences ($p < 0.001$) were observed among genotypes for all examined traits. The highest yield was obtained from the commercial genotype TC-04 (7974.67 kg da^{-1}), followed by TC-02 and TC-03. Among local genotypes, EDR-2 and BAS-2 exhibited promising performance. Correlation analysis revealed that yield was strongly associated with head weight ($r = 0.96$) and head diameter ($r = 0.93$). Principal component analysis based on genotype mean values indicated that the first two components explained 94.8% of the total variation, with yield-related traits contributing most to genotype differentiation. Cluster analysis grouped genotypes according to their performance levels, clearly separating high-yielding commercial genotypes from most local genotypes. The findings suggest that certain local genotypes possess valuable adaptation traits and breeding potential under high-altitude conditions, highlighting the importance of conserving and utilizing local genetic resources for sustainable cabbage production and future breeding programs.

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Introduction

Cabbage (*Brassica oleracea var. capitata* L.) is one of the most widely cultivated vegetable crops worldwide due to its high nutritional value, economic importance, and adaptability to diverse agro-climatic conditions. It is an important source of vitamins, minerals, and dietary fiber and plays a significant role in human nutrition and food security (FAO, 2020).

The productivity and quality of cabbage are strongly influenced by genotype and environmental conditions (Kumar et al., 2021). In particular, high-altitude environments present unique challenges for crop production, including low temperatures, short growing seasons, and large diurnal temperature fluctuations. These conditions can significantly affect plant growth, head formation, and yield, making genotype selection a critical factor for successful production under these conditions (Zhang et al., 2022; Zhang et al., 2023; Ahmad et al., 2021).

Commercial cabbage cultivars, especially hybrid varieties, are generally characterized by high yield potential, uniformity, and improved agronomic performance due to targeted breeding programs. However, their performance may decline under marginal or stress-prone environments such as high-altitude regions. In contrast, local genotypes (landraces) are often well adapted to specific environmental conditions and may possess valuable traits such as tolerance to abiotic stresses, resilience, and stability (Demir et al., 2021; Teshome et al., 2022). In addition to yield performance, local landraces may serve as valuable reservoirs of genetic diversity for traits related to environmental adaptation, stress tolerance, resource-use efficiency, and long-term breeding sustainability.

Despite the recognized importance of both commercial cultivars and local landraces, comparative studies evaluating their performance under high-altitude environments remain relatively scarce (Bhandari et al., 2021).

Previous studies have reported the collection, characterization, and preliminary selection of local cabbage populations in Türkiye (Balkaya and Yanmaz, 2005;

Balkaya and Yanmaz, 2008). However, comprehensive multi-year comparative evaluations of local and commercial cabbage genotypes under the specific high-altitude conditions of Van province are still limited. In particular, information regarding the agronomic performance, morphological variability, and breeding potential of local genotypes under these environmental conditions remains limited. These limitations highlight the need for further comparative and multi-year evaluations under high-altitude environmental conditions.

Van province represents one of the major high-altitude vegetable production areas in eastern Türkiye, characterized by harsh continental climatic conditions, short growing seasons, and large temperature fluctuations, which create unique challenges for cabbage cultivation and genotype adaptation.

The evaluation of genetic variability among cabbage genotypes is essential for both direct cultivation and breeding programs. Morphological and agronomic characterization provides important information on plant performance, while statistical and multivariate analyses such as correlation, principal component analysis (PCA), and cluster analysis allow for a better understanding of relationships among traits and genotype differentiation (Kumar et al., 2022; Raza et al., 2023).

Therefore, this study aimed to comparatively evaluate the agronomic performance and morphological variation of local and commercial cabbage genotypes through a multi-year field experiment and to identify promising genotypes for cultivation and breeding purposes under high-altitude conditions.

Materials and Methods

Materials

This study was conducted to compare the agronomic performance and morphological variation of local and commercial cabbage genotypes under high-altitude conditions of Van province. The research was carried out over two growing seasons during 2024–2025. In the first year (pre-evaluation stage), local cabbage genotypes collected from Van province and its districts were evaluated for preliminary selection. The local genotypes were collected from different districts and rural settlements of Van province, including Bardakçı, Karagündüz, Ovapınar, Ünseli, Dokuzağaç, Taşlıyazı, and other local production areas representing traditional cabbage-growing environments under high-altitude conditions. In this stage, approximately 35 candidate genotypes were examined in terms of morphological and agronomic characteristics.

During the pre-evaluation stage, candidate genotypes were scored using a multi-criteria evaluation approach. This method is widely used in plant breeding and genotype screening studies and allows the simultaneous evaluation of agronomic and morphological traits (Allard, 1999; Yan and Kang, 2003; Balkaya & Yanmaz, 2005; Balkaya & Yanmaz, 2008; Acquaah, 2012). Genotypes were evaluated based on plant development, head formation, yield potential, and visual quality criteria. Visual quality criteria included head compactness, uniformity, external appearance, and marketability. Each trait was weighted and scored accordingly.

The scoring system was based on a 100-point scale, where head weight (25), head characteristics (20), earliness (15), morphological traits (15), adaptation (15), and local value (10) were considered. Local value refers to the traditional cultivation importance, farmer preference, and regional adaptation potential of the genotypes under local production conditions. Based on total scores, genotypes were ranked, and those showing superior performance were included in the main experiment. Genotypes with a total score of 70 points or higher were considered suitable for inclusion in the main experiment. Selection priority was given to genotypes showing superior head formation, yield potential, field adaptation, and visual uniformity under high-altitude conditions. In addition to total score, stability of plant growth and marketable head characteristics were also considered during the final selection process. Detailed pre-selection scores and selection status of all candidate genotypes are presented in Supplementary Table S1.

In the second year, the main experiment was established using 20 local genotypes identified during the preliminary evaluation and 5 commercial cabbage cultivars. The characteristics of all genotypes used in the experiment are presented in Table 1.

The commercial cultivars used in the study included *Green Boy F1* (Syngenta), characterized by earliness; *Megaton F1* (Bejo), known for high yield and mid-season maturity; *Langedijker Bewaar*, a storage-type cabbage cultivar suitable for extended postharvest preservation; *Kilaton F1* (Syngenta), with mid-late maturity and high yield potential; and *Yalova-1*, a widely cultivated cultivar in Türkiye. These cultivars were used as control materials representing earliness, general performance, cold tolerance, yield, and market standards.

All genotypes and cultivars were grown under the same agronomic conditions throughout the experiment.

Experimental Site and Conditions

The study was conducted in Van province at an experimental site located at approximately 1700 m altitude. The region is characterized by a continental climate with a short and cool growing season.

The physicochemical properties of the soil are presented in Table 2. Soil analysis indicated that the soil had a clay loam texture, slightly alkaline reaction, and low organic matter content (Kacar and Katkat, 2011).

During the growing season, temperature gradually increased, while precipitation decreased during summer months. These conditions represent a typical high-altitude cabbage growing environment (Maboko et al., 2022; Zhang et al., 2022).

Experimental Design and Application

The experiment was established according to a randomized complete block design (RCBD) with three replications (Gomez and Gomez, 1984). A total of 25 genotypes (20 local and 5 commercial) were included in the experiment, and all genotypes were present in each replication, resulting in a total of 75 plots. Each plot consisted of two rows, with 10 plants per row, totaling 20 plants per plot. The spacing between plants was 50 cm, and the row spacing was 70 cm.

Plot length was approximately 5 m. Yield per decare (kg da^{-1}) was calculated based on the planting density corresponding to the applied spacing (50 × 70 cm), equivalent to approximately 2857 plants per decare.

Seedlings were grown under controlled nursery conditions and transplanted into the field at the suitable stage. Seeds were sown in seedling trays under greenhouse conditions in early April, and seedlings were transplanted

into the field during the second half of May when plants reached the 4–5 true leaf stage. Before transplanting, the experimental field was prepared using conventional tillage practices. Fertilization was applied uniformly to all plots based on soil analysis results, including basal applications of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O). Additional nitrogen fertilization was applied during vegetative growth stages. Irrigation was performed regularly using furrow irrigation according to crop water requirements throughout the growing season. Standard agronomic practices, including hoeing, weed control, and plant protection measures, were uniformly applied to all experimental plots.

Measured Traits

To evaluate genotype performance, morphological, agronomic, and adaptation-related traits associated with yield and environmental adaptation were examined. Morphological evaluations were conducted according to UPOV (2004) guidelines for cabbage. The evaluated traits included plant height, leaf number, head weight, head diameter, harvest time, and yield per decare, together with additional morphological and observational characteristics related to head structure, adaptation, uniformity, and field performance. Harvesting was performed when cabbage heads reached marketable maturity and compact head structure. Harvest observations were recorded separately for each genotype according to maturity differences under field conditions. All measurements were carried out using the central plants of each plot to eliminate border effects.

Statistical Analysis

The obtained data were analyzed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA). Analysis of variance (ANOVA) was performed to determine differences among genotypes (Gomez and Gomez, 1984). Mean comparisons were conducted using the LSD test.

The statistical model used in the analysis was:

$$Yij = \mu + Gi + Bj + eij \quad (1)$$

where Yij is the observed value, μ is the overall mean, Gi is the effect of genotype, Bj is the effect of block, and eij is the experimental error.

Table S1. Pre-selection scores and evaluation criteria of candidate cabbage genotypes collected from Van province during the preliminary screening stage.

Genotype	HW (25)	HC (20)	E (15)	MT 15)	A (15)	LV (10)	TS	Status
ERC-1	18	15	11	12	12	8	76	Selected
ERC-2	17	14	10	12	11	8	72	Selected
ERC-3	20	16	11	13	12	8	80	Selected
MUR-1	18	15	10	12	11	7	73	Selected
MUR-2	17	14	10	12	11	8	72	Selected
GEV-1	18	15	11	12	12	8	76	Selected
GEV-2	17	14	10	12	11	8	72	Selected
GUR-1	21	17	11	13	13	8	83	Selected
GUR-2	18	15	10	12	11	8	74	Selected
GUR-3	17	15	10	12	11	8	73	Selected
BAS-1	17	14	10	12	11	8	72	Selected
BAS-2	22	18	11	14	13	9	87	Selected
OZA-1	20	16	11	13	12	8	80	Selected
OZA-2	17	14	10	11	11	8	71	Selected
CAT-1	19	15	10	12	12	8	76	Selected
CAT-2	17	14	10	12	11	8	72	Selected
TUS-1	18	15	11	12	12	8	76	Selected
IPE-1	17	14	10	11	11	8	71	Selected
EDR-1	17	15	10	11	11	8	72	Selected
EDR-2	22	18	12	14	13	9	88	Selected
VAN-1	13	12	9	10	10	7	61	Eliminated
VAN-2	14	11	9	10	10	7	61	Eliminated
MUR-3	14	12	10	10	10	7	63	Eliminated
GEV-3	15	13	10	10	10	7	65	Eliminated
BAS-3	13	11	9	10	9	7	59	Eliminated
OZA-3	14	12	10	10	10	7	63	Eliminated
CAT-3	14	12	10	10	10	7	63	Eliminated
TUS-2	15	13	10	10	10	7	65	Eliminated
IPE-2	14	12	10	10	10	7	63	Eliminated
EDR-3	15	13	10	11	10	7	66	Eliminated
VAN-4	13	11	9	10	9	7	59	Eliminated
GUR-4	14	12	10	10	10	7	63	Eliminated
BAS-4	13	11	9	10	9	7	59	Eliminated
OZA-4	14	12	10	10	10	7	63	Eliminated
CAT-4	13	11	9	10	9	7	59	Eliminated

HW: Head Weight; HC: Head Characteristics; E: Earliness; MT: Morphological Traits; A: Adaptation; LV: Local Value; TS: Total Score.

Correlation analysis was performed to evaluate relationships among traits (Steel and Torrie, 1980). Pearson correlation, PCA, and cluster analyses were performed using genotype mean values averaged across the three replications. Principal component analysis (PCA) was conducted based on standardized data to eliminate scale differences among variables and to determine multivariate relationships among genotypes (Jolliffe, 2002). Cluster analysis was conducted using the Ward method based on Euclidean distance to classify genotypes according to their similarity (Ward, 1963).

Results and Discussion

Variation among genotypes

The results of variance analysis revealed statistically significant differences among genotypes for all examined traits including plant height, leaf number, head weight, head diameter, harvest time, and yield ($p < 0.001$). Therefore, detailed mean comparisons were performed using the LSD test (Table 4). These results indicate the presence of substantial genetic variability among the evaluated cabbage genotypes under high-altitude conditions. Such variability is essential for effective selection and breeding programs, particularly under stress-prone high-altitude environments.

Table 1. Characteristics and origin of cabbage genotypes used in the experiment.

Genotype	Group	Source/Origin	Type
ERC-1	Local	Van Merkez (Bardakçı/Karagündüz)	Landrace
ERC-2	Local	Van Merkez (Alaköy/Topaktaş)	Landrace
ERC-3	Local	Van Merkez (Yalınağaç)	Landrace
MUR-1	Local	Van, Muradiye (Ovapınar)	Landrace
MUR-2	Local	Van, Muradiye (Ünseli)	Landrace
GEV-1	Local	Van, Gevaş (Göründü)	Landrace
GEV-2	Local	Van, Gevaş (Dokuzağaç)	Landrace
GUR-1	Local	Van, Gürpınar (Yolaşan)	Landrace
GUR-2	Local	Van, Gürpınar (Taşlıyazı)	Landrace
GUR-3	Local	Van, Gürpınar (Güzelsu)	Landrace
BAS-1	Local	Van, Başkale (Albayrak)	Landrace
BAS-2	Local	Van, Başkale (Bilgeç)	Landrace
OZA-1	Local	Van, Özalp (Sağmalı)	Landrace
OZA-2	Local	Van, Özalp (Aşağı Mollahasan)	Landrace
CAT-1	Local	Van, Çatak (Konalga)	Landrace
CAT-2	Local	Van, Çatak (Korulu)	Landrace
TUS-1	Local	Van, Tuşba (Bardakçı)	Landrace
IPE-1	Local	Van, İpekyolu (Ağzıkara)	Landrace
EDR-1	Local	Van, Edremit (Köşk)	Landrace
EDR-2	Local	Van, Edremit (Süphan)	Landrace
TC-01 (Green Boy F1)	Commercial (control cultivar)	Syngenta	Early hybrid
TC-02 (Megaton F1)	Commercial (control cultivar)	Bejo	Mid-season hybrid
TC-03 (Kilaton F1)	Commercial (control cultivar)	Syngenta	Mid-late hybrid
TC-04 (Langedijker Bewaar)	Commercial	Netherlands	Storage cultivar
TC-05 (Yalova-1)	Commercial (control cultivar)	Türkiye	Standard cultivar

Table 2. Soil physicochemical properties of the experimental site

Parameter	Value
Soil texture	Clay loam
pH	7.6
Organic matter (%)	1.8
Electrical conductivity (dS m^{-1})	0.35
Available N (mg kg^{-1})	42
Available P (mg kg^{-1})	18

Table 3. Mean monthly meteorological conditions recorded during the cabbage growing period (2024–2025) under high-altitude conditions of Van province.

Month	Tmin (°C)	Tmax (°C)	Rainfall (mm)
May	7.4	21.6	42
June	10.2	26.8	28
July	12.5	30.4	12
August	12.0	29.7	9
September	8.3	24.1	18

These findings are consistent with previous studies reporting significant variation among cabbage genotypes due to genetic diversity and genotype × environment interactions (Kumar et al., 2021; Singh et al., 2020; Maboko et al., 2022).

Mean performance of genotypes

Significant differences were observed among genotypes in terms of all measured agronomic traits. Mean comparisons based on LSD test indicated that genotypes differed markedly in yield and yield-related characteristics (Table 4). According to LSD grouping, TC-04 and TC-02 were included in the highest statistical group for yield performance, whereas BAS-2, EDR-2, and GUR-1 formed a similar intermediate performance group among local genotypes. Means followed by the same lowercase letter within each column are not significantly different according to the LSD test at $p < 0.05$.

Among all genotypes, the highest yield was obtained from TC-04 (7974.7 kg da^{-1}), followed by TC-02 (7847.3 kg da^{-1}) and TC-03 (7530.7 kg da^{-1}). These genotypes also exhibited superior performance in head weight and head diameter. Among local genotypes, EDR-2 and BAS-2 showed relatively high yield performance, indicating their potential for use in breeding programs or direct cultivation under high-altitude conditions. In addition to yield performance, BAS-2 and GUR-1 exhibited relatively favorable head diameter, plant vigor, and overall agronomic performance under high-altitude field conditions compared to several other local genotypes.

These characteristics may contribute to their potential use in cabbage breeding programs under high-altitude conditions. In contrast, some local genotypes exhibited lower yield values, suggesting variability in adaptation and performance among local materials.

The superior performance of commercial genotypes observed in this study is consistent with findings reported in previous studies, where hybrid cabbage cultivars showed significantly higher yield and head weight compared to local genotypes (Gupta et al., 2022; Bhandari et al., 2021). This superiority is generally attributed to heterosis, uniformity, and targeted breeding for high yield and adaptability (Tripathi et al., 2022**).**

However, the identification of relatively high-performing local genotypes such as EDR-2 and BAS-2 aligns with studies emphasizing that local landraces often possess valuable adaptive traits such as tolerance to abiotic stress and environmental resilience (Demir et al., 2021; FAO, 2022; Gupta et al., 2022; Teshome et al., 2022). In high-altitude environments, where temperature fluctuations and shorter growing seasons limit crop performance, such adaptive traits become particularly important (Zhang et al., 2022; Zhang et al., 2023). These findings highlight the importance of local germplasm in breeding programs, especially under high-altitude conditions.

Table 4. Mean performance values of agronomic and morphological traits of cabbage genotypes averaged across two growing seasons under high-altitude conditions of Van, Türkiye.

Genotype	Plant Height (cm)	Leaf Number (plant^{-1})	Harvest Time (days)	Head Weight (kg)	Head Diameter (cm)	Yield (kg da^{-1})
TC-04	38.6 a	24.7 a	112 a	4.03 a	27.66 a	7974.67 a
TC-02	37.9 ab	24.1 ab	109 ab	3.84 ab	25.65 b	7847.33 a
TC-03	36.8 bc	23.8 ab	108 ab	3.59 bc	24.40 bc	7530.67 b
EDR-2	35.7 cd	22.9 bc	106 bc	3.33 cd	24.26 bc	7058.00 c
BAS-2	35.5 cd	22.7 bc	105 bc	3.37 cd	24.72 bc	7054.33 c
GUR-1	35.1 cd	22.4 bc	105 bc	3.35 cd	24.28 bc	6996.33 c
OZA-1	34.4 de	21.9 cd	104 bc	3.22 de	23.08 cd	6901.33 c
ERC-3	34.0 de	21.5 cd	103 cd	3.15 de	22.99 cd	6800.00 c
CAT-1	33.6 de	21.3 de	102 cd	3.13 de	21.69 de	6705.33 d
TUS-1	33.4 de	21.1 de	102 cd	3.10 de	23.05 cd	6673.00 d
GEV-1	33.2 de	21.0 de	101 cd	3.08 de	22.92 cd	6621.33 d
GUR-2	32.7 ef	20.8 de	101 cd	2.97 ef	22.49 cd	6462.33 d
TC-05	32.5 ef	20.5 de	100 de	3.04 de	22.09 d	6452.33 d
MUR-1	32.1 ef	20.1 ef	100 de	2.93 ef	22.05 d	6364.00 e
EDR-1	31.9 ef	20.0 ef	99 de	2.97 ef	21.85 de	6328.67 e
OZA-2	31.2 fg	19.8 ef	98 ef	2.81 fg	20.71 ef	6304.00 e
ERC-1	31.0 fg	19.7 ef	98 ef	2.91 ef	21.00 ef	6264.67 e
GEV-2	30.7 gh	19.4 fg	97 ef	2.70 gh	21.20 ef	6231.33 e
IPE-1	30.5 gh	19.2 fg	97 ef	2.70 gh	21.50 de	6210.33 e
CAT-2	29.8 hi	18.9 fg	96 fg	2.47 hij	19.51 fg	5968.67 f
ERC-2	29.5 hij	18.6 fg	96 fg	2.42 hij	20.16 ef	5937.67 f
MUR-2	29.2 ij	18.4 fg	95 fg	2.31 jk	19.59 fg	5927.33 f
GUR-3	29.0 ij	18.2 fg	95 fg	2.55 hi	19.37 fg	5891.67 f
TC-01	28.7 j	18.0 fg	94 g	2.54 hi	19.53 fg	5876.33 f
BAS-1	27.9 k	17.5 g	93 g	2.18 k	18.31 g	5578.67 g
LSD ($p<0.05$)	2.14	1.82	4.3	0.24	1.85	412.6
CV (%)	6.8	5.9	4.6	7.2	5.8	6.9

Means followed by the same lowercase letter within each column are not significantly different according to the LSD multiple comparison test at $p < 0.05$.

Recent studies have also emphasized that local Brassica germplasm may provide valuable adaptive traits for sustainable production under environmentally challenging conditions. Similar findings were reported by Hasan et al. (2021) and Zhang et al. (2023), who highlighted the importance of stress-adapted cabbage genotypes for improving productivity and resilience under variable environmental conditions.

Table 5. Pearson correlation coefficients among agronomic and morphological traits of cabbage genotypes based on genotype mean values averaged across two growing seasons.

Trait	Plant Height (cm)	Leaf Number (plant^{-1})	Harvest Time (days)	Head Weight (kg)	Head Diameter (cm)	Yield (kg da^{-1})
Plant Height (cm)	1.000	0.917**	0.747**	0.907**	0.906**	0.929**
Leaf Number (plant^{-1})	0.917**	1.000	0.782**	0.898**	0.891**	0.898**
Harvest Time (days)	0.747**	0.782**	1.000	0.711**	0.727**	0.695**
Head Weight (kg)	0.907**	0.898**	0.711**	1.000	0.933**	0.956**
Head Diameter (cm)	0.906**	0.891**	0.727**	0.933**	1.000	0.933**
Yield (kg da^{-1})	0.929**	0.898**	0.695**	0.956**	0.933**	1.000

Correlation coefficients are based on genotype mean values averaged across two growing seasons and three replications. Correlation coefficients were significant at $p < 0.01$ according to Pearson correlation analysis.

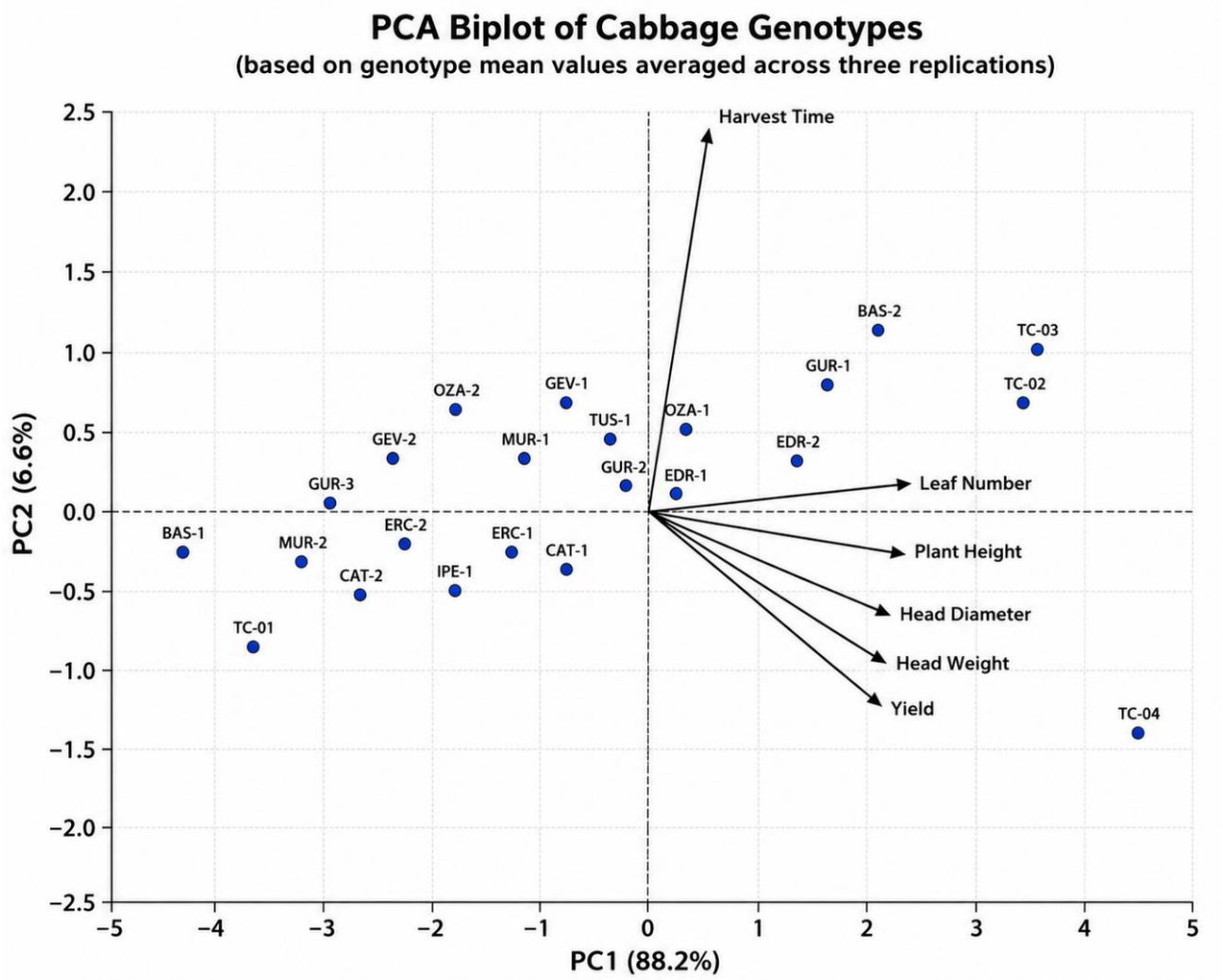

Figure 1. PCA biplot of 25 cabbage genotypes based on genotype mean values averaged across three replications. The first two principal components (PC1 and PC2) explained 94.8% of the total variation, with yield-related traits contributing most strongly to genotype differentiation under high-altitude conditions.

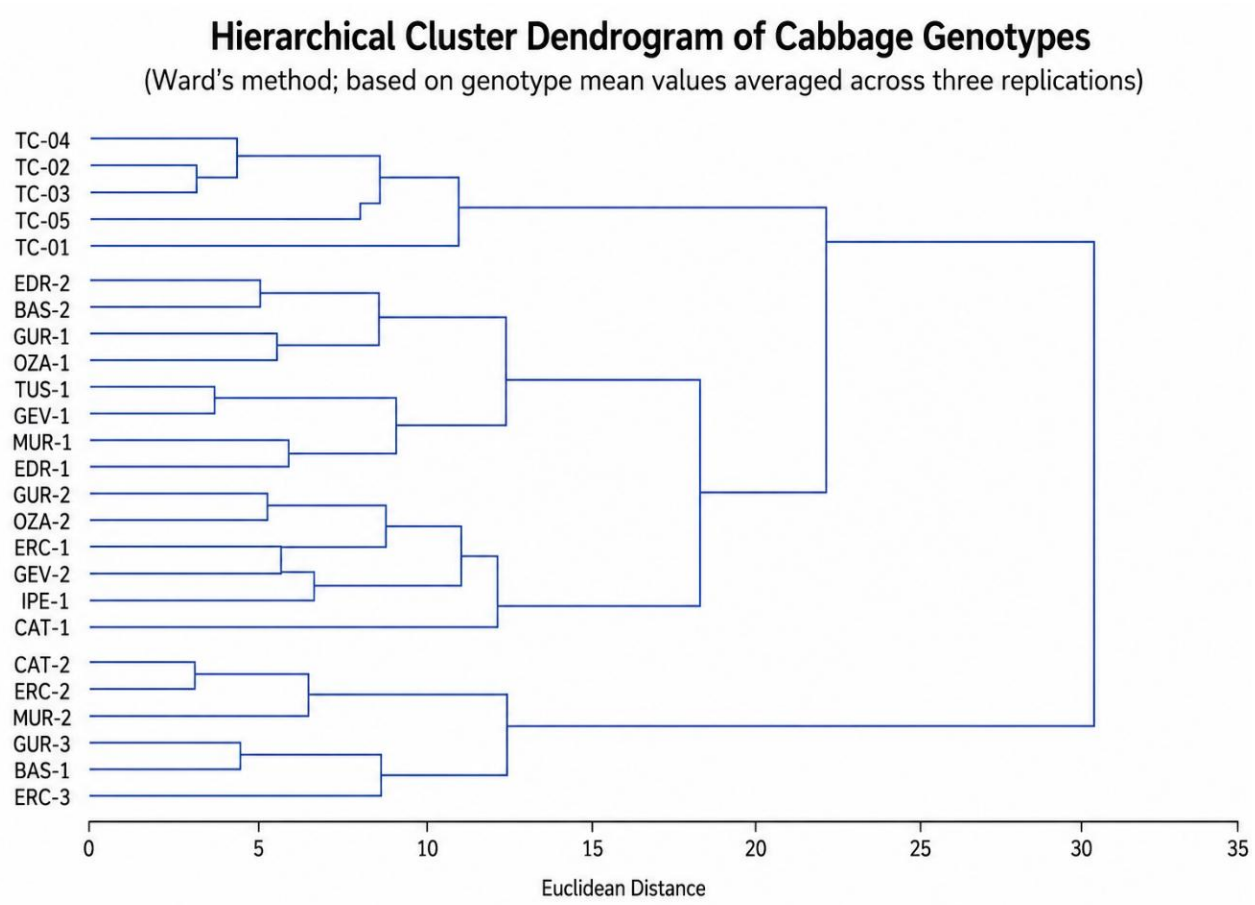

Figure 2. Hierarchical cluster dendrogram of 25 cabbage genotypes generated using Ward's method based on Euclidean distance calculated from genotype mean values averaged across three replications. High-yielding commercial cultivars were clearly separated from most local genotypes, while EDR-2 and BAS-2 showed closer association with the commercial cluster.

Relationships among traits

Correlation analysis revealed statistically significant positive relationships among most of the examined traits (Table 5). Yield showed a very strong positive correlation with head weight ($r = 0.956$, $p < 0.01$), indicating that head weight is one of the primary determinants of yield performance. This finding is consistent with previous studies (Kumar et al., 2021; Singh et al., 2020), which reported similar relationships. This can be explained by the direct contribution of head biomass to total yield.

Yield also exhibited significant positive correlations with plant height ($r = 0.929$, $p < 0.01$), head diameter ($r = 0.933$, $p < 0.01$), and leaf number ($r = 0.898$, $p < 0.01$), suggesting that vigorous vegetative growth contributes positively to yield formation. These findings suggest that larger and more vigorous plants tend to produce higher yields. Harvest time showed a relatively moderate positive correlation with yield ($r = 0.695$), indicating that later genotypes generally tend to have higher productivity. Lower harvest time values indicated earlier maturity, which may provide agronomic advantages under short growing season conditions typical of high-altitude environments.

These results are in agreement with previous studies reporting strong positive relationships between yield and head-related traits in cabbage (Kumar et al., 2021; Singh et al., 2020; Hasan et al., 2021).

Similar relationships between vegetative growth parameters and yield have also been reported in recent correlation studies (Maboko et al., 2022; Gupta et al., 2022).

Principal component analysis (PCA)

The PCA was conducted using genotype mean values averaged across the three replications in order to obtain reliable multivariate classification of cabbage genotypes under high-altitude conditions. Principal component analysis revealed that the first principal component (PC1) explained 88.2% of the total variation, while the second component (PC2) accounted for 6.6%. The first two principal components (PC1 and PC2) explained 94.8% of the total variation among cabbage genotypes, indicating that yield-related traits contributed most strongly to genotype differentiation under high-altitude conditions (Figure 1).

PC1 was strongly associated with yield, head weight, plant height, and head diameter, indicating that these traits are the main contributors to genotype differentiation.

The PCA biplot based on genotype mean values clearly shows that high-yielding commercial genotypes are located on the positive side of PC1, closely associated with yield and head weight, while most local genotypes are distributed on the opposite side (Figure 1).

However, some local genotypes were positioned close to commercial ones, indicating their relatively favorable performance and adaptation under high-altitude conditions. These findings are consistent with previous multivariate analyses in cabbage and Brassica species, where PCA effectively separated genotypes based on yield and morphological traits (Raza et al., 2023; Zhang et al., 2022; Kumar et al., 2022). The high proportion of explained variance (>94%) observed in this study indicates that the evaluated traits sufficiently represent overall genotype performance.

Cluster analysis

Hierarchical cluster analysis grouped the cabbage genotypes into distinct clusters according to their morphological and agronomic characteristics (Figure 2). The hierarchical clustering analysis was performed based on genotype mean values calculated from the three replications, thereby minimizing the influence of plot-level environmental variation on genotype grouping. High-yielding commercial genotypes (TC-02, TC-03, and TC-04) were grouped in the same cluster, while most local genotypes formed separate clusters. Notably, some local genotypes such as EDR-2 and BAS-2 were grouped closer to commercial genotypes, indicating their potential value for breeding and adaptation studies under high-altitude conditions. These clustering patterns are consistent with previous studies, where commercial genotypes clustered together due to similar breeding backgrounds, while local genotypes exhibited wider distribution reflecting genetic diversity (Tripathi et al., 2022; Zhang et al., 2023). The wide distribution of local genotypes across clusters highlights their genetic variability, which is crucial for long-term breeding and adaptation strategies. The clustering pattern obtained in the hierarchical dendrogram was largely consistent with the PCA results. Genotypes positioned close to each other in the PCA biplot were generally grouped within the same clusters in the dendrogram analysis. In particular, high-yielding commercial cultivars such as TC-02, TC-03, and TC-04 were clearly separated from most local genotypes in both multivariate analyses. Similarly, relatively well-performing local genotypes such as EDR-2 and BAS-2 showed closer relationships with commercial cultivars in both PCA and cluster analysis. These consistent patterns confirm the reliability of the multivariate classification and demonstrate that yield-related traits appeared to be among the major factors influencing genotype grouping under high-altitude conditions.

General evaluation

Overall, the results of this study confirm that although commercial genotypes currently outperform most local genotypes in terms of yield, certain local genotypes exhibit comparable performance and relatively good adaptation under high-altitude conditions. Although commercial cultivars exhibited superior yield performance, local landraces remain highly valuable genetic resources due to their potential adaptive advantages under harsh environmental conditions. Traits such as environmental resilience, local adaptation, stability under temperature fluctuations, and potential tolerance to abiotic stresses may provide important breeding opportunities for sustainable cabbage production in high-altitude regions. Therefore, relatively high-performing local genotypes such as EDR-2 and BAS-2 may serve as valuable parental materials for future breeding programs.

Similar conclusions have been reported in recent studies emphasizing the importance of integrating local germplasm into breeding programs (Demir et al., 2021; FAO, 2022; Gupta et al., 2022).

The identification of relatively high-performing local genotypes under high-altitude conditions highlights the potential of these materials for sustainable agriculture and breeding programs. Recent studies have demonstrated that local Brassica germplasm may serve as an important source of adaptive traits for sustainable vegetable production under environmentally stressful conditions, particularly in marginal environments where commercial cultivars may exhibit reduced stability (Bisht et al., 2021; Li et al., 2022).

Conclusion

This study evaluated the agronomic performance and morphological variation of cabbage genotypes under high-altitude conditions, aiming to identify suitable materials for cultivation and breeding. The results revealed a significant effect of genotype on all evaluated traits, indicating substantial variability among cabbage genotypes and underscoring the importance of genotype selection for improving productivity under diverse environmental conditions.

Commercial cultivars outperformed other genotypes in yield and yield-related traits, confirming the effectiveness of modern breeding strategies. Notably, local genotypes such as EDR-2 and BAS-2 exhibited comparable yield performance and relatively good adaptation under high-altitude conditions, emphasizing the value of local genetic resources for sustainable agriculture. Yield showed strong associations with head weight and head diameter, suggesting that these traits should be prioritized as key selection criteria in cabbage breeding programs.

Multivariate analyses (PCA and cluster analysis) demonstrated that yield-related traits are the primary drivers of genotype differentiation and enabled clear classification of genotypes under high-altitude conditions.

From a practical perspective, high-yielding commercial cultivars can be recommended for immediate cultivation, while local genotypes identified in this study may provide useful genetic material for breeding programs. Integrating high yield potential with local adaptation traits is therefore essential for sustainable cabbage production. In addition to yield performance, local genotypes may provide valuable adaptive traits such as environmental resilience and stability under marginal high-altitude conditions, which are important for long-term sustainable cabbage breeding programs.

Overall, both commercial cultivars and local genotypes identified in this study may contribute to improving productivity and ensure sustainable cabbage production in high-altitude environments.

Declarations

Ethical Approval

This study did not involve any human or animal subjects; therefore, ethical approval was not required.

Plant materials were collected from farmer fields and public areas for research purposes.

Conflict of Interest

The author declares no conflict of interest.

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