PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.10386

eISSN 2348-1900

RESEARCH ARTICLE

Morphological evaluation and yield performance of fifty chilli (*Capsicum frutescens* L.) genotypes in Bangladesh

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Received: 30 June 2025; Accepted: 09 November 2025; Available online: Version 1.0: 26 January 2026

Cite this article: Basunia AK, Hossain MM, Rashid MHA, Rashid MH, Howlader NC. Morphological evaluation and yield performance of fifty chilli (*Capsicum frutescens* L.) genotypes in Bangladesh. Plant Science Today (Early Access). https://doi.org/10.14719/pst.10386

Abstract

Higher yield and superior fruit quality are key targets for genetic improvement and commercial cultivation of chilli. To identify promising lines, 50 chilli (*Capsicum frutescens* L.) genotypes were evaluated for their morphological and yield performance. The study was conducted at the Horticulture Farm and Department of Horticulture at Bangladesh Agricultural University (BAU), Mymensingh, from October 2021 to September 2022. A randomized complete block design (RCBD) with 3 replications was employed for the field layout. The genotypes, sourced from various regions of Bangladesh and abroad, exhibited significant variability in growth and yield traits. Genotypes G_{10}, G_{24} and G_{49} exhibited the highest total yield, while G_{34}, G_{28} and G_{15} showed superior fruit traits in terms of weight, length and width. Genotype G_{48}, with the longest peduncles, offered greater harvest efficiency. Principal component analysis (PCA) revealed that 5 components explained 96.73 % of the total variation, primarily influenced by plant height, fruit diameter and fruit number. Non-hierarchical cluster analysis grouped the genotypes into 4 distinct clusters, confirming significant genetic divergence. These findings suggest that G_{10}, G_{24} and G_{49} are ideal for high-yield cultivation, whereas G_{34}, G_{28} and G_{15} are promising for fruit improvement and G_{48} for enhancing harvest efficiency in future breeding programs.

Keywords: chilli genotypes; genetic diversity; morphological traits; principal component analysis; yield performance

Introduction

Chilli (*Capsicum frutescens* L.) is a significant spice crop in Bangladesh and belongs to the genus *Capsicum* and the Solanaceae family. It is prized for its diverse varieties and widespread cultivation. It is predominantly known for its spicy fruits that are rich in antioxidants, pungency, flavor and vitamins (1). Chilli peppers, first domesticated in Central America with archaeological evidence of cultivation in the Tehuacan Valley of Mexico between 400 BCE and 300 CE. In Europe it was introduces in the late 15th century by Spanish explorers following Columbus's voyages. From Europe, they spread rapidly through the West Indies and other parts of the world, ultimately revolutionizing global cuisine (2). During the Age of Discovery, European explorers disseminated chilli peppers to Africa and Asia, with the Portuguese introducing them to the Indian subcontinent in the 16th century, where they quickly became integral to regional cuisines (3). Today, major chilli-producing nations include India, China, Ethiopia, Myanmar, Mexico, Vietnam, Peru, Pakistan, Ghana and Bangladesh (4).

The *Capsicum* genus comprises approximately 30 wild species and 5 domesticated ones, including *Capsicum annuum*, *C. frutescens*, *C. baccatum*, *C. chinense* and *C. pubescens* (5). Chilli peppers have a deep historical and cultural significance, originally cultivated in the Americas for religious rites, warfare and sustenance long before Columbus's arrival, with evidence of chilli pepper use dating back to 7000 BCE in Mexico and Peru (6, 7). Domestication of *C. annuum* began around 5000 BC in Mexico's Tehuacan Valley, leading to its global spread via trade and consumption (8). Over time, chilli peppers have adapted to diverse environmental conditions, including variations in temperature, soil types and rainfall, contributing to their wide agroecological range (9, 10). Additionally, extensive germplasm variability among wild and cultivated *Capsicum* species has facilitated selection for traits such as fruit size, shape, pungency and stress tolerance (11, 12). These adaptations and genetic diversity have enabled chilli peppers to become essential ingredients in cuisines worldwide.

Capsicum frutescens, a species closely related to *C. annuum* and *C. chinense*, originated in South or Central America and spread rapidly throughout tropical and subtropical regions, where it still occurs in the wild. This species, less extensively cultivated than others, includes varieties such as the tabasco pepper, widely used in popular sauces (9–11). In Bangladesh, chilli cultivation spans regions like Comilla, Noakhali, Faridpur, Barisal, Patuakhali and Bogura, contributing significantly to local agriculture and the economy. However, the country faces challenges, including limited availability of high-yielding varieties, low productivity due to reliance on traditional landraces and a lack of systematic characterization of available genotypes (12–14). Moreover, there is an absence of comprehensive studies employing principal component analysis (PCA) and cluster-based approaches to assess genetic divergence

among *C. frutescens* genotypes in Bangladesh. Addressing these limitations is important to identify better genotypes and to support targeted breeding programs aimed at improving yield, fruit quality and harvesting efficiency.

Efforts by the Bangladesh Agricultural Research Institute (BARI) have led to the development of several high-yielding chilli cultivars; however, local production still falls short of national demand. Current research emphasizes improving productivity through breeding programs that exploit the crop's genetic variability and desirable traits (15, 16). Major challenges include biotic stresses from pests such as thrips and diseases like anthracnose, highlighting the need for cultivars with enhanced resistance (17, 18). Consequently, Bangladesh imports substantial quantities of chilli each year to satisfy domestic consumption, underscoring the importance of sustainable production strategies and the development of improved cultivars (19, 20).

Chilli peppers hold a pivotal role in Bangladesh's agricultural sector as well as in global culinary traditions. Their cultivation, spanning from ancient civilizations to modern farming practices, underscores their enduring significance and potential for improvement through advanced breeding and optimized cultivation techniques. Despite their importance, challenges such as low-yielding traditional varieties, limited high-performing genotypes and insufficient genetic characterization persist. Addressing these gaps is essential not only to meet increasing domestic and international demand but also to ensure sustainable and resilient chilli production in Bangladesh and beyond.

Materials and Methods

Experimental site

Field experiments were conducted at the Horticulture Farm and the Department of Horticulture, Bangladesh Agricultural University (BAU), Mymensingh (24°26′ N latitude, 90°15′ E longitude, 18 m above sea level) from October 2021 to September 2022. The study area has a subtropical climate, characterized by high temperature, humidity and rainfall from April to August, followed by cooler and drier conditions with clear sunshine during the remaining months. The experimental field is located on sandy loam soil of the Brahmaputra Floodplain (Agro-Ecological Zone 09) and is classified as non-calcareous dark grey soil (21, 22). Soil samples collected from the experimental site were analyzed at the Department of Soil Science, BAU, Mymensingh and the results are presented in Table 1.

Planting materials and experimental design

The materials used in this study are described in the following sub-sections. A total of 50 chilli genotypes were evaluated in this experiment. Check or control varieties were obtained from the BARI. The selected genotypes were collected from both domestic and international sources within Bangladesh based on their availability and performance reputation. The experiment was laid out following a randomized complete block design (RCBD) with 3 replications. The complete list of chilli genotypes used in the study is provided in Table 2.

Field preparation and chilli production

Seeds of the evaluated germplasm were collected during the harvesting season (October–December 2021) from well-matured and healthy plants grown in farmers' fields of different districts of Bangladesh and other chilli growing countries. For each genotype, fully ripened fruits were randomly selected and seeds were manually extracted, cleaned and shade-dried to maintain viability. The collection period extended over 3 months to ensure representative sampling. After drying, the seeds were packed in airtight containers and stored at room temperature until sowing in the experimental plots. Germination occurred within 3–7 days. Sevin dust was applied to protect against insects. Regular irrigation, weeding and thinning were carried out throughout the crop growth period. Irrigation was provided at 7–10 days intervals depending on soil moisture conditions, while weeding was done twice at 20 and 40 days after sowing (DAS). Thinning was performed once at 15 DAS to maintain uniform plant spacing. Dithane M-45 (2 g/L) was sprayed periodically to prevent fungal infections. The field was ploughed 3–4 times, fertilized as per Fertilizer Recommendation Guide (FRG-2012) and divided into 3 blocks with 150 plots total. Each plot measured 0.5 m × 1.2 m. Thirty-day-old healthy seedlings were transplanted in the afternoon at 50 cm × 50 cm spacing with immediate irrigation. Each plot contained 8 plants. Weeding, top dressing of urea and irrigation every 10th day were performed. Plants were staked and tied to protect them from wind and rain. Fungicides (Dithane M-45, Sondhi), insecticides and micronutrients (Copper, Nutra-Phos, Boron, Sulphur) were applied as needed.

Table 1. Soil characteristics of the experimental plot

Characteristics of soil	BAU Agri-Varsity Humboldt Soil Testing Laboratory
AEZ	AEZ 9: Old Brahmaputra Floodplain under
Soil series	Sonatola series
General soil	Predominantly dark grey, moderately acidic
Parent material	Old Brahmaputra River-borne deposit
Available moisture-holding capacity	Inherently low
The general fertility level	Low to medium
pH	5.53
EC (µs/cm)	1234.67
CO_3^-(ppm)	0.00
HCO_3^- (mg/kg)	177.33
Org. M (%)	1.53
Total N (%)	0.08
P (ppm)	22.79
K (meq/100 g)	0.112
S (ppm)	10.64

[Here, AEZ = Agro-Ecological Zone; EC = Electrical Conductivity; CO_3^- = Carbonate; HCO_3^- = Bicarbonate; Org. M = Organic Matter; N = Nitrogen; P = Phosphorus; K = Potassium; S = Sulfur].

Table 2. List of fifty Chilli genotypes with their source of origin

Genotypes No.	Name of genotypes	Source of origin	Genotypes No.	Name of genotypes	Source of origin
G_1	Mymensingh Local-1	Mymensingh, Bangladesh	G_{26}	Chinese Bona	Kolkata, India
G_2	Rangpur Jhal-1	Bogura, Bangladesh	G_{27}	Hazari Morich	Mymensingh, Bangladesh
G_3	Light Purple Chilli	USA	G_{28}	Hathazari Chilli	Chattogram, Bangladesh
G_4	Mymensingh Local-2	Mymensingh, Bangladesh	G_{29}	Raipuri Chilli	Chattogram, Bangladesh
G_5	White Long Chilli	Mymensingh, Bangladesh	G_{30}	Jethali Morich	Kushtia, Bangladesh
G_6	Bird Chilli-00954	Thailand	G_{31}	Indian- 2	India
G_7	Rangpur Jhal-2	Bogura, Bangladesh	G_{32}	Gazi Morich	Bogura, Bangladesh
G_8	Pepper-01075	Thailand	G_{33}	Brazilian Black Hot Chilli	Brazil
G_9	Indian-1	Tamil Nadu, India	G_{34}	Indian-3	India
G_{10}	Gazipur Local	Gazipur, Bangladesh	G_{35}	Egyptian Chilli	Egypt
G_{11}	Bindu Morich	Mymensingh, Bangladesh	G_{36}	Long Chilli	USA
G_{12}	Current Morich	Mymensingh, Bangladesh	G_{37}	BARI Morich-1, (Check Variety 1)	BARI, Bangladesh
G_{13}	Dhani Morich	Mymensingh, Bangladesh	G_{38}	Malaysian Chilli	Malaysia
G_{14}	Dudh Morich	Mymensingh, Bangladesh	G_{39}	Bird Chilli 02411	Thailand
G_{15}	Kamranga Chilli	Mymensingh, Bangladesh	G_{40}	Indian-4	Tamil Nadu, India
G_{16}	Naga Chilli	Sylhet, Bangladesh	G_{41}	Mymensingh Local-3	Mymensingh, Bangladesh
G_{17}	Bullet Bombai Chilli	Kolkata, India	G_{42}	BARI Morich-2	BARI, Bangladesh
G_{18}	Sri Lankan Chilli	Sri Lanka	G_{43}	BARI Morich-3	BARI, Bangladesh
G_{19}	Chilli Bona IR-8	Kolkata, India	G_{44}	Mymensingh Local 4	Mymensingh, Bangladesh
G_{20}	Satkhira Local Jhal	Sri Lanka	G_{45}	Bullet Lanka	Kolkata, India
G_{21}	Suryamukhi Chilli	Kolkata, India	G_{46}	Long Peppers	Dhaka, Bangladesh
G_{22}	Ak-47 Bullet Chilli	Kolkata, India	G_{47}	Kul Jhal	Satkhira, Bangladesh
G_{23}	Nagraj Chilli	Sylhet, Bangladesh	G_{48}	Bogura Local 1	Bogura, Bangladesh
G_{24}	Thai Rupali Chilli	Thailand	G_{49}	Bogura Local 2	Bogura, Bangladesh
G_{25}	Thai Chilli Pepper	Thailand	G_{50}	Bogura Local 3	Bogura, Bangladesh

Data collection

The height of each plant was measured at 50 % flowering. A meter rule was used to measure the height of the plants from the surface of the soil to the tip of the apical meristem. The average height of 5 randomly selected and healthy plants was considered to represent each germplasm, as is a common practice in germplasm evaluation studies. Since all plants were grown under uniform field conditions with replications, the mean of these representative plants reliably reflects the growth performance of that germplasm. Moreover, several published studies on germplasm characterization have also adopted similar sampling procedures, where measurements from 5–10 plants are sufficient to indicate the varietal potential. The measurements were taken in centimeters (cm) and the data were recorded accordingly. The most extended branch with leaves from the base of the plant was measured towards the direction of North–South and East–West by a meter scale in cm. It was recorded by counting the days from the date of transplanting to 50 % flowering (when the 50 % flower was fully opened in each plot) by observing the plant every morning. Days to 1st fruit set were recorded by counting the days from the date of transplanting to the 1st fruit set by observing the plant every morning.

The number of days required for fruit maturity was recorded by daily observation of the plants. Stem diameter was measured using a vernier caliper at the midpoint of each plant and the average of all measurements per germplasm was used to represent stem thickness. Fruit length and width were measured in cm using a vernier caliper. For each variety, 10 fruits were randomly selected and their length (from pedicel attachment to apex) and width (at the widest part) were recorded; the average values represented the germplasm. Pedicel length was measured similarly and the mean of 5 fruits was used.

Branch length was measured using a meter scale in both North–South and East–West directions, recording the most extended branches with leaves. The number of fruits per plant was determined by counting fruits from 5 randomly selected plants at different harvesting dates at the mature green stage; the average was used. Fruit development duration was recorded by counting the days from first fruiting to final harvest.

Fresh fruit weight per plant was calculated by dividing the total fresh weight of fruits from 5 randomly selected plants by the total number of fruits, expressed in grams (g). For dry weight, fruits were washed, oven-dried at 75 °C for 3 days and weighed with an electric balance; the mean weight of 5 fruits represented the germplasm. Seed number per fruit was determined by counting seeds from 5 randomly selected fruits and the average was calculated. One thousand seeds were weighed from 5 randomly selected samples and the mean was recorded in g. Dry yield per plot was estimated by multiplying the average dry yield per plant by the total number of plants in the plot, expressed in kilograms (kg). Dry yield per hectare was calculated by multiplying the average dry yield per plant by the total number of plants per hectare, expressed in tons (t).

Statistical analysis

Data for the different traits were statistically analyzed using the MSTAT-C Statistical Package. Means for all treatments were calculated and a variance analysis (ANOVA) for each parameter was conducted. Differences among means were compared using Duncan's Multiple Range Test (DMRT) at 5 % and 1 % probability levels. PCA was performed using the correlation matrix to examine relationships among traits, with components having eigenvalues greater than one considered for interpretation based on their contribution to total variance. The contribution of morphological traits to genetic divergence was assessed using the first 2 principal components (PC). Additionally, genotypes were clustered using a non-hierarchical method in GENSTAT, where an iterative algorithm refined groupings by transferring genotypes to improve clustering criteria until no further improvement was possible (3).

Results and Discussion

Plant height and branching pattern

Significant variation was observed among the chilli genotypes in both plant height and the number of primary branches at the full fruiting stage. The tallest plants were recorded in G_{11} (111.33 cm), followed by G_4 (110.33 cm) and G_5 (109.33 cm), whereas G_{37} exhibited the shortest stature (49.67 cm). Similarly, the number of primary branches per plant varied notably, with G_{18} producing the highest count [12], followed by G_{11} [10.67] and G_{21} [10.33], while G_{27} had the fewest [4.33]. As all genotypes were grown under uniform environmental conditions and management practices, these differences reflect inherent genetic variability. Genotypes with greater branch numbers tended to form larger canopies, indicating enhanced plant architecture and vigor. Such variation in growth habits and branching pattern has implications for canopy management, light interception and potential fruit yield (Table 3).

Leaf area

Leaf area varied considerably among the chilli genotypes. The largest canopy was observed in G_1(0.54 m^2) and G_5 (0.52 m^2), whereas G_{44} exhibited the smallest canopy (0.06 m^2). Larger canopy sizes can enhance sunlight interception, potentially improving photosynthetic efficiency and overall plant vigor. Since all genotypes were grown under uniform environmental conditions and management practices, the observed differences can be attributed primarily to genetic variability (Table 3).

Fruit length

Fruit length exhibited considerable variation among the chilli genotypes. The longest fruit was recorded in genotype G_{28} (18.07 cm), while the shortest was observed in G_9(2.99 cm). Genotypes with longer fruits tend to possess a higher number of seeds, which can contribute to yield potential. All genotypes were cultivated under uniform environmental conditions and agronomic management, indicating that the observed differences in fruit length are largely attributable to genetic factors (Table 3).

Peduncle length

Peduncle length varied notably among the 50 chilli genotypes. The longest peduncle was observed in G_{48}(6.87 cm), while G_{15} had the shortest (2.40 cm). Differences in peduncle length can affect fruit positioning and ease of harvest, with longer peduncles potentially facilitating mechanical or manual harvesting. Since all genotypes were grown under uniform environmental and cultural conditions, the variation is primarily attributable to genetic differences (Table 3).

Fruit diameter

Fruit diameter exhibited considerable variation among the chilli genotypes. The widest fruit diameter was recorded in genotype G_{15} (47.24 mm), while the narrowest was observed in G_{13} (7.93 mm). Genotypes with wider fruit diameters tend to contain a greater number of seeds, which may contribute to higher yield potential. All genotypes were cultivated under identical environmental conditions and management practices, indicating that the variation in fruit diameter was primarily due to genetic differences. These findings align with previous reports, confirming substantial genetic diversity in fruit diameter among chilli varieties (Table 3).

Number of fruits per plant

The number of fruits per plant showed marked variation among the chilli genotypes. The highest fruit count was recorded in genotype G_{47} (447.51), while the lowest was observed in G_2 (19.03). Genotypes producing more fruits per plant contribute significantly to overall yield potential. As all genotypes were grown under uniform environmental and cultural conditions, the observed differences can be attributed to genetic variability (Table 3).

Single fruit weight

Single fruit weight varies substantially among the chilli genotypes. The heaviest fruit was recorded in G_{34} (13.60 g), while G_{14} produced the lightest (1.19 g). Genotypes with heavier fruits can contribute significantly to total yield. Since all genotypes were grown under uniform conditions, the observed differences are primarily due to genetic variation (Table 3).

Fruit weight per plant

Fruit weight per plant showed considerable variation across genotypes. G_{10} produced the highest yield per plant (1.21 kg), whereas G_{15}had the lowest (0.04 kg). Yield per plant is influenced by factors such as fruit number, individual fruit weight and fruit size. As all genotypes were cultivated under identical conditions, the differences likely reflect inherent genetic variability (Table 3).

Yield per hectare (t/ha)

Significant differences in yield per hectare were observed among the chilli genotypes. Yields ranged from 0.06 t/ha (G_{15}, Kamranga Chilli) to 1.93 t/ha (G_{10}, Gazipur Local). High-yielding genotypes such as G_{10}, G_{24} and G_{34} demonstrate strong potential for improved production under high-density planting and optimized agronomic practices. Conversely, low yields in G_{15}, G_{36} and G_{44} may result from poor adaptability or susceptibility to biotic stress (Table 3).

Principal component analysis in chilli genotypes

Eigenvalues and latent vectors corresponding to 9 PCs and their respective contributions to total variation were obtained through PCA (Table 4). The first 5 components together explained 96.73 % of the total variation. Specifically, PC1 accounted for 28.36 %, PC2 for 18.10 %, PC3 for 13.99 %, PC4 for 11.14 % and PC5 for 8.67 % of the variance. The remaining components cumulatively explained only 8.74 % (Fig. 1a), indicating that the first 5 components captured most of the variability among genotypes.

Non-hierarchical clustering and intra-cluster distances

With the application of the covariance matrix for non-hierarchical clustering, 50 chilli genotypes were grouped into 4 different clusters

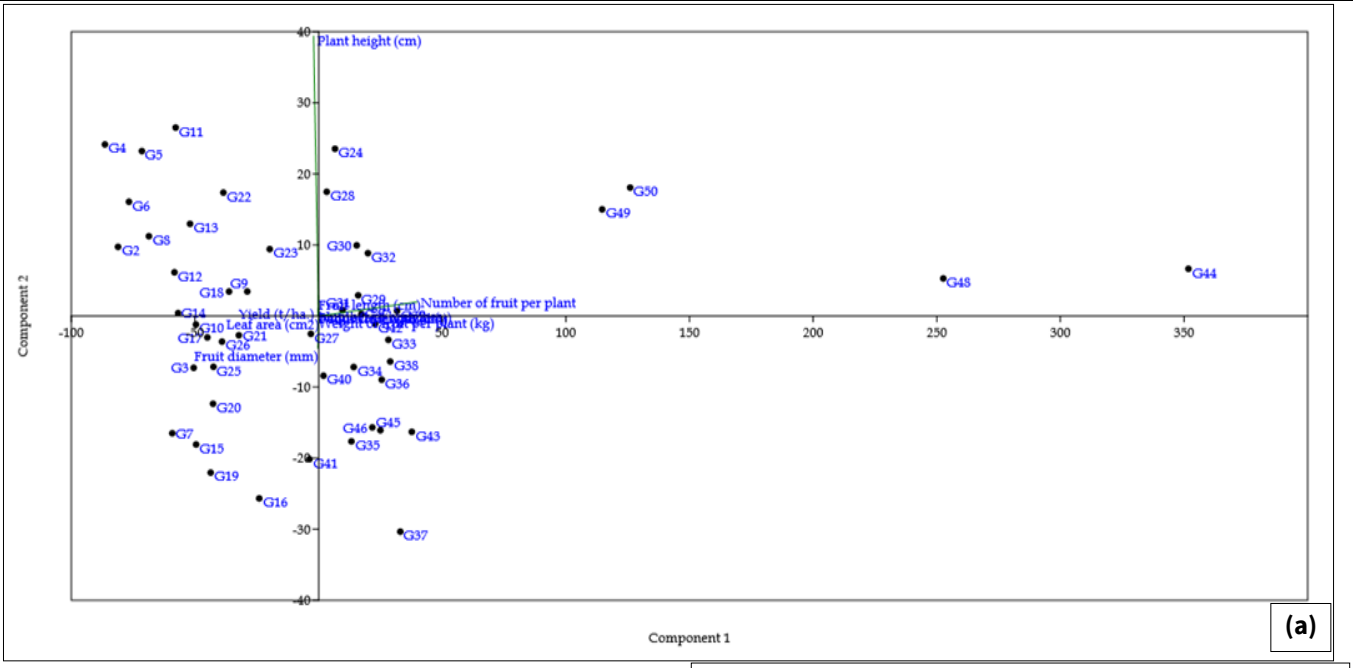
Table 3. Genotypic mean of selected chilli genotypes

Genotypes	Plant height (cm)	No. of branches	Leaf area (cm^2)	Peduncle length (cm)	Fruit length (cm)	Fruit diameter (mm)	No. of fruit per plant	Single fruit weight (g)	Weight of fruit (kg/plant)	Yield (t/ha)
G_1	89.67^{a-e}	8.67^{a-e}	0.54^{a}	3.17^{cd}	12.00^{de}	12.78^{b}	24.94^{d}	5.99^{fg}	0.71^{b-e}	1.13^{b-e}
G_2	95.33^{a-e}	7.33^{a-e}	0.42^{a-f}	2.77^{cd}	12.27^{c-e}	10.26^{b}	22.36^{d}	3.65^{i}	0.56^{d-i}	0.90^{d-i}
G_3	77.00^{a-f}	8.00^{a-e}	0.29^{c-l}	3.03^{cd}	8.93^{h-l}	11.36^{b}	52.06^{cd}	2.18^{n-p}	0.54^{d-k}	0.86^{d-k}
G_4	110.33^{a}	6.33^{b-e}	0.45^{a-d}	3.90^{cd}	10.57^{e-j}	10.59^{b}	17.82^{d}	2.16^{n-p}	0.41^{h-p}	0.66^{h-p}
G_5	109.33^{a}	5.00^{de}	0.53^{ab}	2.80^{cd}	7.30^{k-q}	14.28^{b}	32.74^{cd}	3.18^{i-m}	0.62^{c-h}	0.99^{c-h}
G_6	101.67^{a-c}	8.33^{a-e}	0.30^{b-k}	3.00^{cd}	8.90^{h-m}	9.77^{b}	27.10^{d}	3.44^{ij}	0.36^{i-q}	0.57^{i-p}
G_7	68.00^{b-f}	5.33^{de}	0.26^{d-l}	3.27^{cd}	9.37^{f-k}	10.00^{b}	42.93^{cd}	3.37^{i-k}	0.37^{i-p}	0.60^{i-p}
G_8	96.33^{a-e}	8.33^{a-e}	0.24^{d-l}	3.50^{cd}	9.10^{g-k}	9.41^{b}	34.91^{cd}	2.55^{m-o}	0.35^{i-q}	0.56^{i-p}
G_9	88.67^{a-e}	5.67^{c-e}	0.21^{e-l}	2.45^{d}	2.99^{t}	24.97^{b}	74.42^{cd}	7.99^{d}	0.39^{i-p}	0.62^{i-p}
G_{10}	83.33^{a-f}	6.00^{b-e}	0.32^{a-j}	4.03^{b-d}	15.93^{ab}	17.66^{b}	53.36^{cd}	3.06^{i-m}	1.21^{a}	1.93^{a}
G_{11}	111.33^{a}	10.67^{ab}	0.24^{d-l}	4.17^{a-d}	14.87^{bc}	16.06^{b}	46.56^{cd}	8.97^{c}	0.47^{f-m}	0.75^{f-m}
G_{12}	90.67^{a-e}	8.00^{a-e}	0.36^{a-j}	4.13^{b-d}	7.60^{k-q}	8.84^{b}	44.97^{cd}	4.52^{h}	0.69^{b-f}	1.10^{b-f}
G_{13}	97.33^{a-d}	9.67^{a-d}	0.24^{d-l}	3.03^{cd}	6.03^{n-s}	7.93^{b}	51.63^{cd}	0.51^{r}	0.21^{o-t}	0.34^{o-s}
G_{14}	85.33^{a-f}	8.33^{a-e}	0.14^{j-l}	3.50^{cd}	3.63st	10.14^{b}	46.17^{cd}	1.19^{qr}	0.13^{q-t}	0.21^{p-t}
G_{15}	70.33^{b-f}	7.33^{a-e}	0.31^{b-k}	2.40^{d}	7.50^{k-q}	47.24^{b}	52.97^{cd}	1.81^{pq}	0.04^{t}	0.06^{t}
G_{16}	59.33^{ef}	8.33^{a-e}	0.40^{a-h}	3.88^{cd}	5.82^{p-s}	29.61^{b}	77.82^{cd}	6.44^{ef}	0.49^{e-l}	0.78^{e-l}
G_{17}	81.67^{a-f}	10.33^{a-c}	0.21^{a-d}	2.86^{cd}	5.07^{q-t}	15.67^{b}	57.86^{cd}	5.69^{g}	0.35^{i-r}	0.55^{i-r}
G_{18}	87.00^{a-f}	12.00^{a}	0.22^{d-l}	4.03^{b-d}	11.93^{d-f}	13.56^{b}	66.93^{cd}	3.26^{i-l}	0.52^{e-k}	0.84^{e-k}
G_{19}	61.67^{d-f}	6.00^{b-e}	0.39^{a-i}	3.43^{cd}	8.67^{h-m}	10.06^{b}	58.16^{cd}	3.36^{i-k}	0.40^{h-p}	0.63^{h-p}
G_{20}	71.33^{b-f}	6.00^{b-e}	0.46^{a-d}	3.13^{cd}	10.97^{e-i}	10.82^{b}	59.62^{cd}	3.31^{i-l}	0.32^{j-r}	0.52^{j-r}
G_{21}	80.67^{a-f}	10.33^{a-c}	0.23^{d-l}	3.23^{cd}	7.40^{k-q}	10.86^{b}	70.57^{cd}	3.29^{i-l}	0.30^{k-s}	0.49^{k-s}
G_{22}	101.33^{a-c}	8.67^{a-e}	0.52^{a-c}	5.03^{a-d}	11.27^{e-h}	13.99^{b}	65.35^{cd}	3.19^{i-m}	0.50^{e-l}	0.80^{e-l}
G_{23}	92.33^{a-e}	8.33^{a-e}	0.27^{d-l}	2.73^{cd}	7.63^{k-q}	10.58^{b}	83.65^{cd}	1.31^{q}	0.56^{d-j}	0.89^{d-j}
G_{24}	105.00^{ab}	5.67^{c-e}	0.35^{a-j}	3.80^{cd}	16.03^{fab}	15.25^{bb}	110.71^{cd}	11.35^{b}	0.88^{b}	1.41^{b}
G_{25}	76.67^{a-f}	5.33^{de}	0.33^{a-j}	3.07^{cd}	11.63^{d-g}	12.32^{b}	60.05^{cd}	4.75^{h}	0.45^{f-n}	0.72^{f-m}
G_{26}	80.00^{a-f}	5.67^{c-e}	0.35^{a-j}	3.20^{cd}	11.00^{e-i}	10.81^{b}	63.68^{cd}	2.53^{m-o}	0.32^{k-r}	0.51^{k-r}
G_{27}	79.33^{a-f}	4.33^{e}	0.24^{d-l}	3.17^{cd}	10.79^{e-i}	10.81^{b}	99.64^{cd}	3.42^{ij}	0.44^{g-o}	0.70^{g-o}
G_{28}	99.00^{a-d}	6.33^{b-e}	0.27^{d-l}	3.87^{cd}	18.07^{a}	15.41^{b}	107.08^{cd}	7.89^{d}	0.56^{d-j}	0.89^{d-j}
G_{29}	84.00^{a-f}	7.67^{a-e}	0.25^{d-l}	3.40^{cd}	6.31^{m-r}	10.30^{b}	119.03^{cd}	3.28^{i-l}	0.50^{e-k}	0.80^{e-k}
G_{30}	91.00^{a-e}	6.33^{b-e}	0.28^{d-l}	5.20^{a-c}	6.97^{k-q}	9.57^{b}	118.77^{cd}	3.31^{i-l}	0.43^{h-p}	0.69^{h-p}
G_{31}	82.33^{a-f}	8.33^{de}	0.29^{b-l}	4.27^{a-d}	8.53^{i-n}	13.69^{b}	112.62^{cd}	6.73^{e}	0.43^{h-p}	0.69^{h-p}
G_{32}	89.67^{a-e}	7.00^{b-e}	0.18^{d-l}	3.70^{cd}	8.07^{j-p}	10.22^{b}	123.26^{cd}	3.55^{i}	0.26^{l-t}	0.42^{l-t}
G_{33}	77.33^{a-f}	5.00^{de}	0.37^{a-j}	2.73^{cd}	6.37^{l-r}	11.52^{b}	130.92^{cd}	2.13^{n-p}	0.31^{k-s}	0.50^{k-s}
G_{34}	74.00^{a-f}	7.67^{a-e}	0.27^{d-l}	3.40^{cd}	13.97^{b-d}	18.01^{b}	116.74^{cd}	13.60^{a}	0.67^{b-g}	1.08^{b-g}
G_{35}	63.67^{d-f}	5.33^{de}	0.21^{e-l}	3.83^{cd}	5.47^{p-t}	11.43^{b}	115.26^{cd}	2.63^{l-o}	0.31^{k-s}	0.50^{k-s}
G_{36}	71.33^{b-f}	7.67^{a-e}	0.08^{kl}	3.67^{cd}	8.90^{h-m}	9.58^{b}	127.92^{cd}	1.61^{pq}	0.13^{q-t}	0.20^{q-t}
G_{37}	49.67^{f}	7.00^{b-e}	0.24^{d-l}	2.73^{cd}	8.67^{h-m}	12.30^{b}	134.36^{cd}	4.74^{h}	0.34^{i-r}	0.55^{i-r}
G_{38}	74.00^{a-f}	6.33^{b-e}	0.08^{kl}	4.23^{a-d}	5.90^{o-s}	9.90^{b}	131.47^{cd}	2.10^{op}	0.11^{r-t}	0.18^{r-t}
G_{39}	81.00^{a-f}	8.00^{a-e}	0.20^{e-l}	4.77^{a-d}	7.37^{k-q}	11.19^{b}	134.62^{cd}	3.31^{i-l}	0.23^{n-t}	0.37^{n-t}
G_{40}	75.00^{a-f}	5.00^{de}	0.16^{i-l}	3.47^{cd}	4.30^{r-t}	24.47^{b}	104.60^{cd}	8.55^{cd}	0.76^{b-d}	1.22^{b-d}
G_{41}	62.00^{d-f}	5.00^{de}	0.39^{a-i}	3.03^{cd}	8.80^{h-m}	14.13^{b}	98.16^{cd}	6.31^{e-g}	0.46^{f-n}	0.74^{f-m}
G_{42}	79.33^{a-f}	6.00^{b-e}	0.41^{a-g}	3.13^{cd}	8.83^{h-m}	9.80^{b}	125.60^{cd}	7.96^{d}	0.39^{h-p}	0.63^{h-p}
G_{43}	63.33^{d-f}	8.33^{a-e}	0.16^{i-l}	2.73^{cd}	8.47^{i-o}	9.64^{b}	139.70^{cd}	2.69^{k-o}	0.20^{p-t}	0.32^{p-t}
G_{44}	71.33^{b-f}	5.33^{de}	0.06^{l}	3.80^{cd}	5.70^{p-s}	12.11^{b}	454.58^{a}	1.51^{pq}	0.05^{t}	0.09^{t}
G_{45}	65.00^{c-f}	5.67^{c-e}	0.25^{d-l}	2.67^{cd}	5.57^{p-t}	14.42^{b}	127.08^{cd}	3.07^{i-m}	0.25^{m-t}	0.40^{m-t}
G_{46}	64.67^{c-f}	7.00^{b-e}	0.19^{f-l}	3.80^{cd}	15.57^{ab}	12.99^{b}	123.79^{cd}	1.80^{pq}	0.08st	0.13^{s-t}
G_{47}	81.33^{a-f}	5.33^{de}	0.17^{h-l}	2.60^{cd}	8.93^{h-l}	11.32^{a}	120.18^{cd}	2.80^{j-m}	0.05^{t}	0.08^{j-m}
G_{48}	74.33^{a-f}	7.00^{b-e}	0.26^{d-l}	6.87^{a}	12.69^{c-e}	13.27^{b}	355.47a^{b}	6.17^{e-g}	0.38^{i-p}	0.61^{i-p}
G_{49}	91.00^{a-e}	7.00^{b-e}	0.36^{a-j}	6.63^{ab}	11.90^{d-f}	12.87^{b}	218.17^{b-d}	7.92^{d}	0.82^{bc}	1.31^{bc}
G_{50}	93.33^{a-e}	8.67^{a-e}	0.44^{a-e}	3.07^{cd}	11.27^{e-h}	9.57^{b}	229.64^{bc}	3.72^{i}	0.45^{g-o}	0.71^{g-o}
LSD (0.01)	37.39	4.94	0.24	2.72	2.62	5.13	201.10	0.69	0.23	0.21
LSD (0.05)	28.24	3.73	0.18	2.06	1.98	7.41	151.91	0.52	0.18	0.17
Level of significance	**	**	**	**	**	**	**	**	**	**
CV (%)	11.21	12.24	8.31	5.56	13.25	5.62	12.50	7.48	13.28	15.71

[In a column, means followed by similar letter(s) did not differ significantly by LSD test. Here, **= Significant at 1 % level of probability; G_1: Mymensingh Local-1, G_2: Rangpur Jhal-1, G_3: Light Purple Chilli, G_4: Mymensingh Local-2, G_5: White Long Chilli, G_6: Bird Chilli-00954, G_7: Rangpur Jhal-2, G_8: Pepper-01075, G_9: Indian-1, G_{10}: Gazipur Local, G_{11}: Bindu Morich, G_{12}: Current Morich, G_{13}: Dhani Morich, G_{14}: Dudh Morich, G_{15}: Kamranga Chilli, G_{16}: Naga Chilli, G_{17}: Bullet Bombai Chilli, G_{18}: Sri Lankan Chilli, G_{19}: Chilli Bona IR-8, G_{20}: Satkhira Local Jhal, G_{21}: Suryamukhi Chilli, G_{22}: Ak-47 Bullet Chilli, G_{23}: Nagraj Chilli, G_{24}: Thai Rupali Chilli, G_{25}: Thai Chilli Peper, G_{26}: Chinese Bona, G_{27}: Hazari Morich, G_{28}: Hathazari Chilli, G_{29}: Raipuri Chilli, G_{30}: Jethali Morich, G_{31}: Indian- 2, G_{32}: Gazi Morich, G_{33}: Brazilian Black Hot Chilli, G_{34}: Indian-3, G_{35}: Egyptian Chilli, G_{36}: Long Chilli, G_{37}: BARI Morich-1 (Check Variety 1), G_{38}: Malaysian Chilli, G_{39}: Bird Chilli 02411, G_{40}; Indian-4, G_{41}: Mymensingh Local-3, G_{42}: BARI Morich-2, G_{43}: BARI Morich-3, G_{44}: Mymensingh Local 4, G_{45}: Bullet Lanka, G_{46}: Long Peppers, G_{47}: Kul Jhal, G_{48}: Bogura Local 1, G_{49}: Bogura Local 2, G_{50}: Bogura Local 3].

Table 4. Principal component analysis of selected chilli genotypes

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	2.552	28.360	28.360
2	1.629	18.099	46.459
3	1.259	13.992	60.451
4	1.002	11.138	71.589
5	0.780	8.672	80.261
6	0.611	6.792	87.053
7	0.469	5.213	92.266
8	0.402	4.469	96.736



(Table 5). Cluster analysis grouped the traits into 2 distinct clusters. Cluster I comprised 8 closely related parameters (G_2, G_3, G_4, G_6, G_8, G_9, G_{11} and G_{13}), whereas Cluster II included 3 parameters (plant height, fruit diameter and number of fruits per plant) which were distantly located, indicating their divergence. These findings justify the clustering pattern and also confirm the PCA results (Fig. 1b). Cluster distances, denoted by the average inter- and intra-cluster distances, are the approximate measure of the cluster divergence (Table 5). The intra- and inter-cluster distance presented in Fig. 2a. The varieties belonging to the distant clusters could be used for further base population improvement.

Construction of a scatter diagram

Based on the values of PC score, a 2-dimensional scatter diagram, using component score 1 as X-axis and component score as Y-axis, was constructed (Fig. 2b). The position of the chilli genotypes in the scatter diagram was apparently distributed. The distribution of 10 selected characters based on their PC score and superimposed with clusters indicated that the genotypes were apparently distributed into 4 groups. The scattered diagram for the selected growth and yield parameters of 2 clusters revealed that the parameters of plant height, fruit diameter and number of fruits per plant were distantly located,

Table 5. Cluster analysis of selected characters of chilli genotyes

Stage	Cluster combined		Coefficients
	Cluster I	Cluster II	
1	2	9	1.39
2	5	8	191.41
3	3	6	638.92
4	2	5	1379.44
5	2	3	4031.70
6	2	4	132510.99
7	1	7	311241.85
8	1	2	987622.63

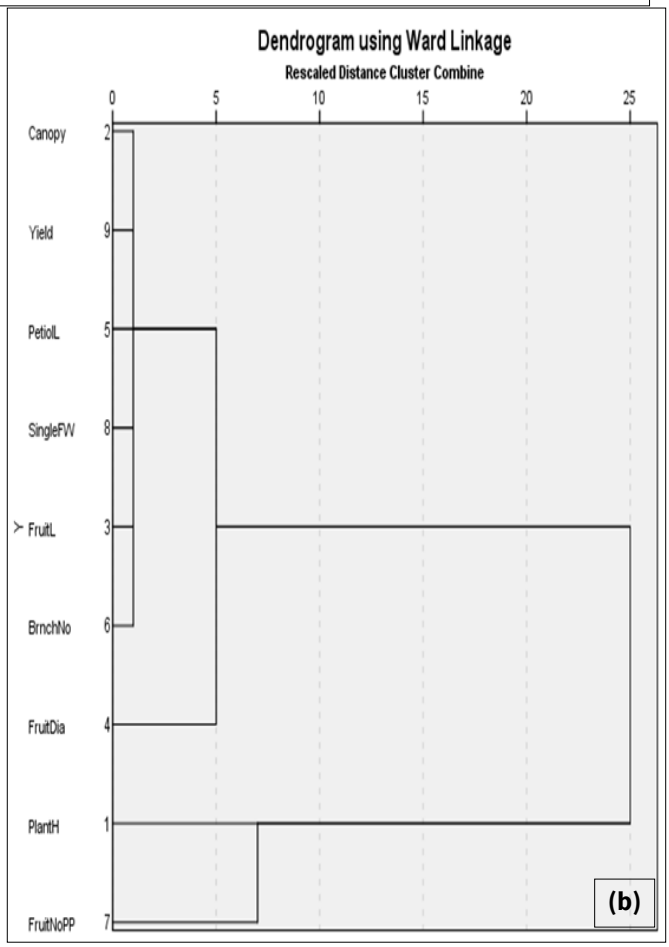


Fig. 1. (a) PCA Bi-Plot of selected chilli genotypes; (b) dendrogram based on summarized data on differentiation among 10 morphological and yield contributing parameters according to Ward's method.

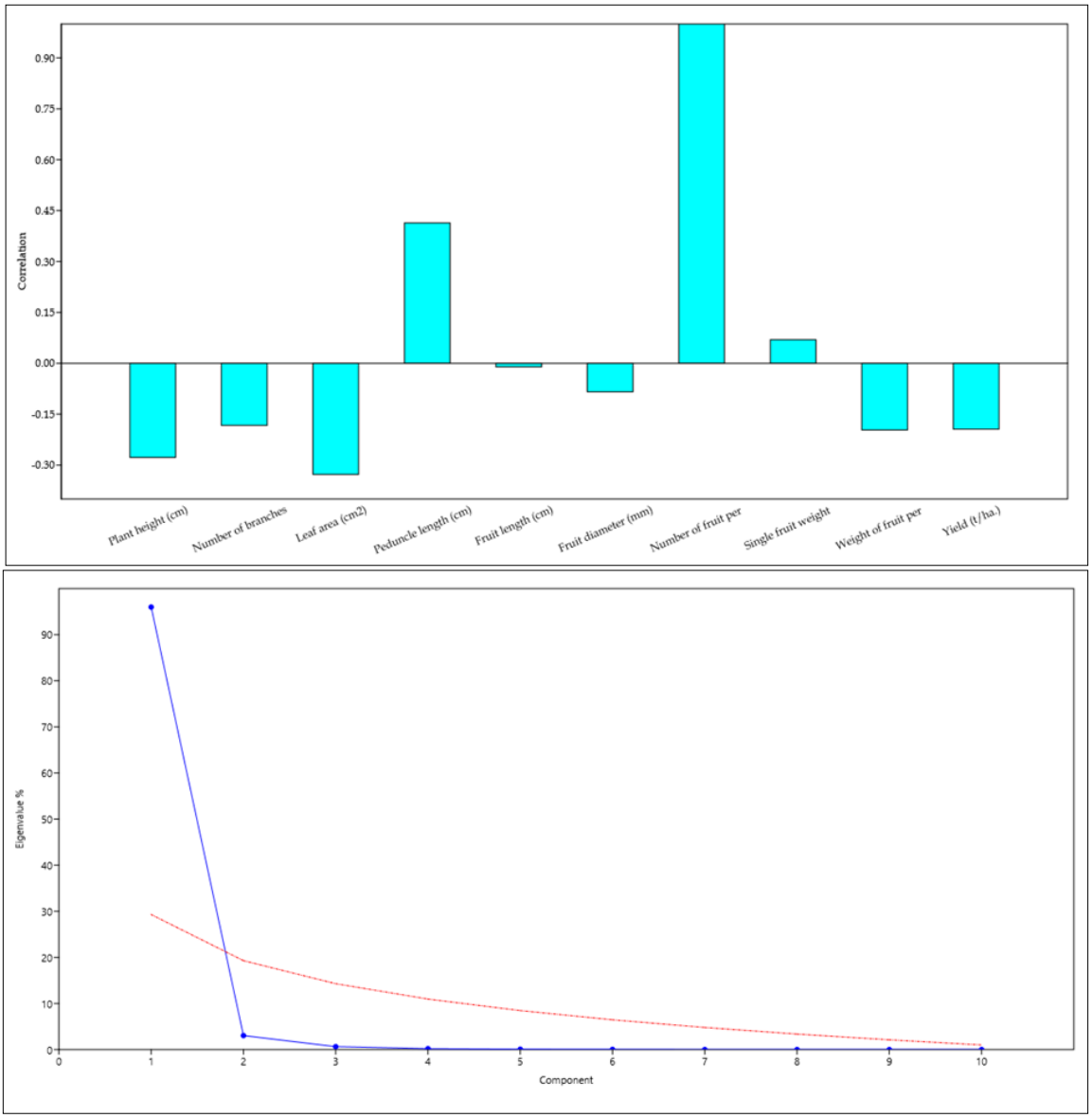


Fig. 2. PCA analysis (a) Loading plot; (b) Scree plot.

which suggests they are more diverged from the rest of the selected parameters. In Fig. 3, the dendrogram analysis illustrates the genetic relationships and performance among 50 chilli genotypes.

Fruit yield per plant (g)

Fruit yield per plant ranged widely, with G_{10} producing 1205.3 g and G_{15} only 36.0 g (Fig. 4). This variation highlights the influence of genetic potential, branch number and fruit size on overall productivity, even under uniform management conditions.

Discussion

The evaluation of 50 chilli genotypes revealed substantial morphological and yield-related variability, reflecting the existence of significant genetic diversity among the tested varieties. Such diversity is critical for breeding programs aimed at yield enhancement and adaptation to specific agro-ecological zones.

Plant height exhibited considerable variation among the genotypes, with G_{11} reaching 111.33 cm and G_{37} being the shortest at 49.67 cm. These differences are primarily attributed to genetic control of internode length and overall growth habit. Taller plants may capture light more effectively but are more prone to lodging, whereas shorter plants are easier to manage under cultivation (23).

Branching also varied significantly, with G_{18} producing the highest number of primary branches [12], supporting greater canopy expansion and potentially increasing fruiting sites, while G_{27} had the fewest branches [4.33]. Branching is influenced by apical dominance and hormonal regulation and higher branching generally enhances the number of floral sites, which can contribute to increased yield under optimal conditions (24–26). Leaf area ranged from 0.06 m^2 in G_{44} to 0.54 m^2 in G_1. Larger leaf areas facilitate greater photosynthetic activity, supporting improved biomass accumulation and fruit yield (27). Fruit traits also showed substantial variability: G_{28} produced the longest fruits (18.07 cm) and G_9 the shortest (2.99 cm), while G_{15} recorded the widest fruit diameter (47.24 mm) and G_{13} the narrowest (7.93 mm). Longer and wider fruits are often preferred in market classes and are typically associated with higher seed numbers and fruit weight. These traits are polygenic and influenced by both genetic factors and hormonal regulation during fruit development (28–30).

Variation in peduncle length (2.40 cm to 6.87 cm) affects fruit visibility, harvestability and market appeal. Genotypes with longer peduncles, such as G_{48}, may be preferred for easier hand harvesting, aligning with the earlier observations, noted the impact of peduncle length on fruit detachment and handling (31). G_{47} had the highest

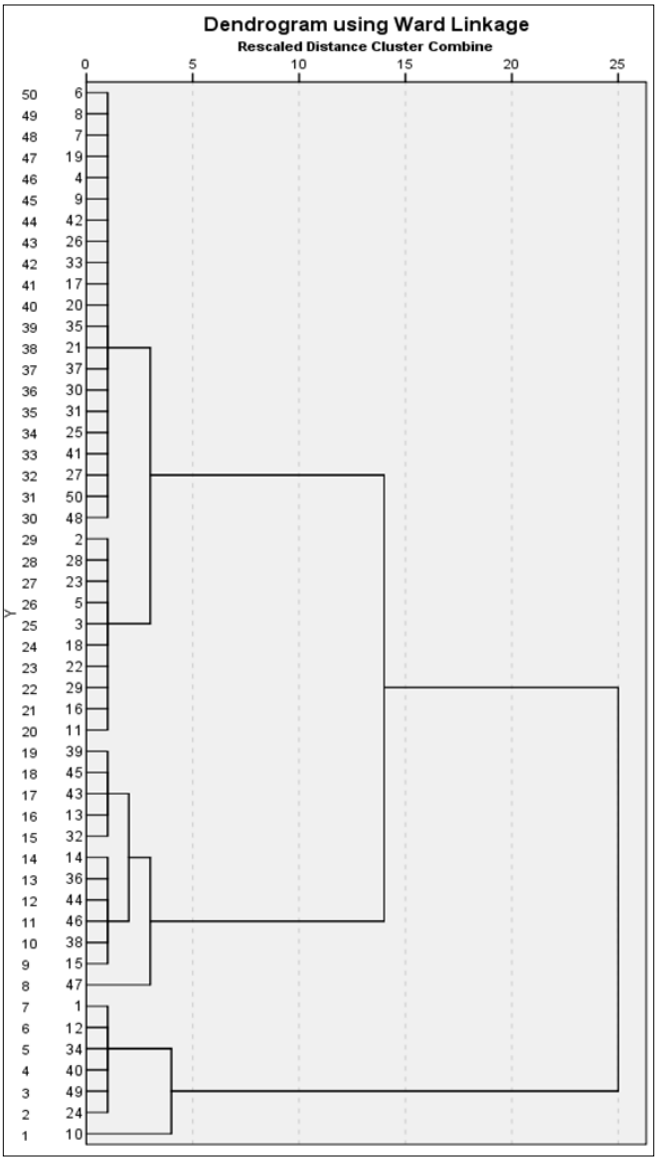


Fig. 3. Dendrogram analysis among fifty chilli genotypes based on their performance.

fruit count (447.51), whereas G_2 had the lowest (19.03). Fruit count is a major yield determinant, affected by flowering habits, pollination success and branching. A higher fruit number does not always translate into greater yield unless accompanied by sufficient fruit size and weight (32, 33). The heaviest individual fruits were from G_{34} (13.60 g) and the highest total yield per plant was found in G_{10} (1.21 kg). Lighter fruits were associated with G_{14} and G_{15}, which also recorded the lowest yields. These yield differences underscore the importance of selecting for both fruit size and number in breeding programs. The combined effects of fruit number, size and weight determine overall productivity (34–36). PCA revealed that 8 PC accounted for 96.73 % of the total variation. The first component alone explained 28.36 %, mainly contributed by plant height, fruit diameter and number of fruits per plant. This suggests that these traits are the most influential in differentiating among genotypes and should be emphasized in selection indices.

Non-hierarchical clustering grouped the 50 chilli genotypes into 2 distinct clusters, highlighting the genetic diversity within the varieties. Cluster II comprised genotypes with distinct plant height and fruit characteristics, representing a valuable resource for hybrid development. The wide intra- and inter-cluster distances indicate considerable potential for heterosis if genotypes from divergent clusters are crossed (37–43). The scatter diagram corroborated the PCA and clustering results, illustrating the dispersion of genotypes across trait combinations. Genotypes occupying distinct quadrants in the scatter plot may carry unique alleles for yield-related traits and can be prioritized for selection and breeding. The observed phenotypic variation in growth and yield traits under uniform cultivation conditions confirms the presence of broad genetic diversity. Such variation is critical for future improvement programs aimed at developing high-yielding, stable and adaptable chilli varieties. Traits including fruit number, single fruit weight and fruit diameter contributed strongly to total yield and should be considered key selection criteria in breeding strategies.

Conclusion

This study evaluated 50 chilli genotypes for their growth, fruit quality and yield-related traits. Substantial differences were observed among genotypes in vegetative vigor, branching pattern, fruit morphology and yield components. Genotype G_{11} recorded the tallest plants (111.33 cm), while G_{18} exhibited the highest number of primary branches (12). Superior fruit traits were identified in G_{34} (heaviest fruit, 13.60 g), G_{28} (longest fruit, 18.07 cm) and G_{15} (widest diameter, 47.24 mm). Genotype G_{10}demonstrated the highest fruit yield per plant (1.21 kg), while G_{47} had the highest fruit count per plant (447.51), suggesting strong yield potential. Additionally, G_{48} with the longest peduncles (6.87 cm) showed advantages for manual harvest. Based on these results, G_{10} is recommended for commercial cultivation, while G_{34}, G_{28} and $G_{15}$are valuable for fruit improvement programs. G_{48} may be exploited for enhancing harvest ability in breeding pipelines.

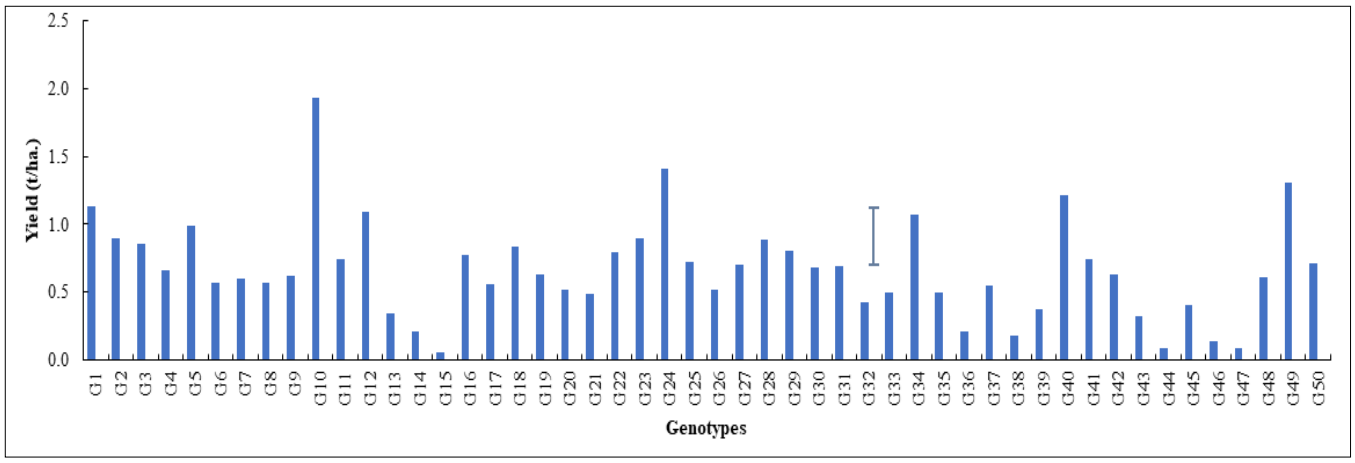


Fig. 4. Yield of different chilli genotypes. The vertical bar represents LSD at 5 % level of probability.

Acknowledgements

The authors extends their sincere thanks to the Ministry of Education, Government of the People's Republic of Bangladesh, for the support during the research trial.

Authors' contributions

AKB contributed to conceptualization, methodology, investigation, data curation, statistical analysis and writing of the original draft. MMH was involved in conceptualization, supervision, resources, validation and writing-review and editing. MHAR contributed through supervision and writing-review and editing. MHR contributed to supervision, validation and writing-review and editing. NCH contributed to investigation, data curation, visualization and writing of the original draft. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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