

# DUS based morphological evaluation of genetic divergence in bell pepper (*Capsicum annuum* L. var. *grossum* Sendt.)

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## Research Article

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## Abstract

Bell pepper is one of the most important Solanaceous vegetable crops in the world and it exhibits great variability in terms of fruit size, shape and colour which are the most important marketable traits in bell pepper alongwith other morphological traits. Hence, an attempt was made, in this study to evaluate the genetic diversity in 34 advanced breeding lines/genotypes of bell pepper, along with two common check varieties (California Wonder and Solan Bharpur) using 41 agro-morphological descriptors (24 qualitative and 17 quantitative) based on DUS (Distinctness, Uniformity and Stability). The present study was carried out during 2022-23 and 2023-24 at Dr YS Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh. Significant variation was observed among various morphological traits with maximum diversity index value of 1.01 for fruit shape in longitudinal section. In terms of fruit yield per plant, it was discovered that the genotypes UHF-CAP-108, UHF-CAP-119, IIHR-131, UHF-CAP-106 and UHF-CAP-113 significantly outperformed the better check variety, Solan Bharpur, with desirable medium-sized, dark green, glossy and 3–4 lobed fruits. Principal component analysis (PCA) demonstrated that 83.08% of the total variance was contributed by the first six components, in which genotypes were characterized. Through multivariate analysis, the study effectively examined genetic divergence and classified the 34 advanced breeding lines/genotypes into five distinct clusters. The highest inter-cluster distance was observed between cluster III and cluster V, highlighting considerable diversity among the genotypes within these groups suggesting potential for broad enhancements in subsequent crop breeding programs.

## INTRODUCTION

Bell pepper (*Capsicum annuum* L. var. *grossum* Sendt.), sometimes referred to as sweet pepper, green pepper, vegetable paprika or Shimla Mirch is cultivated all over the world for its flavour, colour and delicate taste (Devi et al. 2015). It is indigenous to Mexico with South America as its centre of diversity (Gonzalez and Bosland 1991). The market value of bell pepper is determined by its diverse fruit shapes (elongate, almost spherical, triangular, campanulate and blocky) and colours (red, yellow, green, white, purple and orange) (Banerjee et al. 2023). However, consumers typically prefer blocky, square, thick-fleshed, three to four lobed and non-pungent fruits. It is a valuable source of vitamins, carotenoids and phenolic compounds and its extensive morphological diversity in fruit color, shape and size renders it an appealing subject for breeding initiatives and hybrid breeding programmes.

In varietal registration and seed certification systems, the assessment of Distinctness, Uniformity, and Stability (DUS) traits is an essential requirement for the identification and protection of new cultivars. These descriptors not only ensure varietal distinctness but also aid in preliminary germplasm evaluation and classification (Arti et al. 2022; Das et al. 2024). Morphological characterization based on DUS provides a cost-effective method for initial diversity estimation. However, due to environmental influence on phenotypic expression, such characterization is increasingly being supported by multivariate statistical analyses, including cluster analysis and principal component analysis (PCA) to decipher trait interrelationships and major axes of variation (Mishra et al. 2024). PCA helps to identify the most discriminating traits contributing to overall diversity and allows efficient grouping of accessions for selection and breeding (Anuradha et al. 2024). In most bell pepper studies, fruit-related attributes such as fruit length, diameter, weight and pericarp thickness tend to contribute the most to total phenotypic variation, forming the first few principal components that capture the majority of diversity within populations (Arti et al. 2022; Mishra et al. 2024).

Despite considerable progress, several regional collections of *C. annuum* L. var. *grossum* Sendt. remain inadequately characterized. Hence, comprehensive diversity assessment through DUS based trait scoring, multivariate analyses and PCA modeling can reveal unutilized variation essential for breeding programs aimed at yield improvement, stress tolerance and quality enhancement (Toker et al. 2025). The present study, therefore, aims to characterise advanced breeding lines/genotypes of bell pepper using standardized DUS descriptors, supported by PCA and cluster analysis, to identify the principal traits contributing to variability and to aid in the selection of promising genotypes for future breeding and varietal development.

## MATERIALS AND METHODS

### Plant materials and experimental site

The experiment was carried out at Dr YS Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh during 2022-23 and 2023-24 in a Randomized Complete Block Design (RCBD) with three replications using thirty-four advanced breeding lines/ genotypes of bell pepper alongwith two standard check varieties i.e., California Wonder and Solan Bharpur (Table 1). Transplanting was done on 13th April, 2022 and harvested in the last week of July 2022 and for second year crop, transplanting was done on 17th April, 2023 and harvested in first week of August 2023. The standard cultural practices for healthy crop development of bell pepper was followed as recommended in the “Package of Practices for Vegetable Crops” by Dr YS Parmar, University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh (Anonymous 2016).

Table 1  
List of advanced breeding lines/ genotypes of bell pepper alongwith their source of collection used in the study

| Sr. No. | Name of genotype(s)       | Source(s) of collection                                |
|---------|---------------------------|--------------------------------------------------------|
| 1.      | UHF-CAP-101               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 2.      | UHF-CAP-102               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 3.      | UHF-CAP-103               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 4.      | UHF-CAP-104               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 5.      | UHF-CAP-105               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 6.      | UHF-CAP-106               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 7.      | UHF-CAP-107               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 8.      | UHF-CAP-108               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 9.      | UHF-CAP-109               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 10.     | UHF-CAP-110               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 11.     | UHF-CAP-111               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 12.     | UHF-CAP-112               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 13.     | UHF-CAP-113               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 14.     | UHF-CAP-114               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 15.     | UHF-CAP-115               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 16.     | UHF-CAP-116               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 17.     | UHF-CAP-117               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 18.     | UHF-CAP-118               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 19.     | UHF-CAP-119               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 20.     | UHF-CAP-120               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 21.     | UHF-CAP-121               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 22.     | UHF-CAP-122               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 23.     | UHF-CAP-123               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 24.     | UHF-CAP-124               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 25.     | UHF-CAP-125               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 26.     | UHF-CAP-126               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 27.     | UHF-CAP-127               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 28.     | UHF-CAP-128               | Department of Vegetable Science, UHF, Nauni, HP, India |
| 29.     | IIHR-131                  | ICAR-IIHR, Hessarghata, Bangalore, India               |
| 30.     | IIHR-132                  | ICAR-IIHR, Hessarghata, Bangalore, India               |
| 31.     | IIHR-133                  | ICAR-IIHR, Hessarghata, Bangalore, India               |
| 32.     | IIHR-134                  | ICAR-IIHR, Hessarghata, Bangalore, India               |
| 33.     | Solan Bharpur (check)     | Department of Vegetable Science, UHF, Nauni, HP, India |
| 34.     | California Wonder (check) | ICAR-IARI, Regional Station, Katrain, HP, India        |

## Morphological characterization and multivariate analyses

The data were recorded for 25 qualitative and 17 quantitative traits in 34 genotypes of bell pepper as per the distinctiveness, uniformity and stability (DUS) guidelines as outlined by the Protection of Plant Varieties and Farmers' Rights Authority (PPV& FRA) for bell pepper during both years of study. The genetic divergence, principal component analysis (PCA) and diversity index was also worked out in the current research to assess the genetic diversity present in different bell pepper genotypes. The observations were recorded on ten randomly selected plants of each replication.

## Data analysis

Mean performance for different horticultural traits in addition to morphological observations were recorded for two years, 2022-23 and 2023-24. The Shannon diversity index (H) was calculated for each descriptor using PAST (PAleontological Statistics) software (Hammer et al. 2001). Multivariate analysis was done for 17 quantitative traits using Mahalanobis D2 statistic (Mahalanobis 1936), followed by grouping of genotypes into various clusters by Ward's method using R software (Ward 1963). Principal component analysis (PCA) and all the graphical figures were also generated using R software.

## RESULTS AND DISCUSSION

### Morphological characterization based on DUS

Sufficient variation was observed among the genotypes of bell pepper for most of the morphological traits studied except for some traits such as hypocotyl colour of the seedling, stem shape, leaf colour, leaf pubescence, petal colour, fruit bearing habit, fruit colour intensity at maturity, absence of fruit blossom end appendage and seed colour with zero value of Shannon Diversity Index (H) suggesting very little to no variation present for these traits among the bell pepper genotypes under study as it serves as a useful tool for capturing the degree of variability in different morphological characteristics. Excluding these traits, the value of Shannon Diversity Index (H) ranged between 0.10 (fruit curvature intensity) to 1.01 (fruit shape in longitudinal section) with mean value and range of 0.44 and 1.01, respectively (Table 2). Based on these morphological descriptors, breeders can select desirable lines of bell pepper for breeding programmes and further crop improvement. Similar results were also reported by other researchers, viz. Ferdousi et al. (2021), Arti et al. (2022), Sahin et al. (2022) and Sood et al. (2023).

Table 2  
Morphological characterisation for 41 DUS traits in 34 bell pepper genotypes alongwith their diversity indices

| Trait                                         | State                   | Frequency | Relative frequency (%) | Diversity index (H) |
|-----------------------------------------------|-------------------------|-----------|------------------------|---------------------|
| Seedling: hypocotyl colour                    | Absent                  | 0         | 0.00                   | 0.00                |
|                                               | Present                 | 34        | 100                    |                     |
| Plant habit                                   | Spreading               | 9         | 26.47                  | 0.78                |
|                                               | Semi- upright           | 23        | 67.65                  |                     |
|                                               | Upright                 | 2         | 5.88                   |                     |
| length of main stem (cm)                      | Short (upto 5 cm)       | 0         | 0.00                   | 0.66                |
|                                               | Medium (5.01-10 cm)     | 21        | 61.76                  |                     |
|                                               | Long (> 10 cm)          | 13        | 38.24                  |                     |
| length of first internode (cm)                | Very short (up to 1 cm) | 0         | 0.00                   | 0.90                |
|                                               | Short (1.01- 2 cm)      | 0         | 0.00                   |                     |
|                                               | Medium (2.01-4 cm)      | 21        | 61.76                  |                     |
|                                               | Long (4.01-6 cm)        | 4         | 11.76                  |                     |
|                                               | Very long (> 6 cm)      | 9         | 26.47                  |                     |
| anthocyanin colouration of nodes              | Absent                  | 8         | 23.53                  | 0.55                |
|                                               | Present                 | 26        | 76.47                  |                     |
| intensity of anthocyanin colouration of nodes | Weak                    | 14        | 41.17                  | 0.97                |
|                                               | Medium                  | 7         | 20.59                  |                     |
|                                               | Strong                  | 5         | 14.70                  |                     |
| Plant height (cm)                             | Short (< 40 cm)         | 0         | 0.00                   | 0.65                |
|                                               | Medium (40.01-60 cm)    | 22        | 64.71                  |                     |
|                                               | Tall (> 60 cm)          | 12        | 35.29                  |                     |
| Plant spread (cm)                             | Narrow (< 50 cm)        | 32        | 94.12                  | 0.22                |
|                                               | Medium (50.01–100 cm)   | 2         | 5.88                   |                     |
|                                               | Broad (> 100 cm)        | 0         | 0.00                   |                     |
| Stem pubescence                               | Absent                  | 29        | 85.29                  | 0.42                |
|                                               | Present                 | 5         | 14.71                  |                     |
| Intensity of stem pubescence                  | Sparse                  | 5         | 14.71                  | 0.28                |
|                                               | Medium                  | 0         | 0.00                   |                     |
|                                               | Strong                  | 0         | 0.00                   |                     |
| Stem shape                                    | Round                   | 0         | 0.00                   | 0.00                |
|                                               | Angled                  | 34        | 100                    |                     |
|                                               | Flat                    | 0         | 0                      |                     |
| Leaf length (cm)                              | Short (< 4 cm)          | 0         | 0                      | 0.22                |
|                                               | Medium (4.01-8 cm)      | 2         | 5.88                   |                     |
|                                               | Long (> 8 cm)           | 32        | 94.12                  |                     |
| Leaf width (cm)                               | Narrow (< 3 cm)         | 1         | 2.94                   | 0.70                |
|                                               | Medium (3.01-5 cm)      | 24        | 70.58                  |                     |
|                                               | Broad (> 5 cm)          | 9         | 26.47                  |                     |
| Leaf colour                                   | Green                   | 34        | 100                    | 0.00                |
|                                               | Purple                  | 0         | 0.00                   |                     |
|                                               | Green with purple tinge | 0         | 0.00                   |                     |

| Trait                                              | State                   | Frequency | Relative frequency (%) | Diversity index (H) |
|----------------------------------------------------|-------------------------|-----------|------------------------|---------------------|
| Intensity of green leaf colour                     | Purple with green tinge | 0         | 0.00                   | 0.90                |
|                                                    | Light                   | 4         | 11.76                  |                     |
|                                                    | Medium                  | 9         | 26.47                  |                     |
|                                                    | Dark                    | 21        | 61.76                  |                     |
| Leaf shape                                         | Lanceolate              | 29        | 85.30                  | 0.49                |
|                                                    | Ovate                   | 4         | 11.76                  |                     |
|                                                    | Broad elliptic          | 1         | 2.94                   |                     |
| Leaf pubescence                                    | Absent                  | 34        | 100                    | 0.00                |
|                                                    | Present                 | 0         | 0.00                   |                     |
| Petal colour                                       | White                   | 34        | 100                    | 0.00                |
|                                                    | Yellowish green         | 0         | 0.00                   |                     |
|                                                    | Purple                  | 0         | 0.00                   |                     |
|                                                    | Others (specify)        | 0         | 0.00                   |                     |
| Anther colour                                      | Yellow                  | 4         | 11.76                  | 0.36                |
|                                                    | Pale blue               | 0         | 0.00                   |                     |
|                                                    | Purple                  | 30        | 88.24                  |                     |
|                                                    | Others (specify)        | 0         | 0.00                   |                     |
| Days to 50% flowering                              | Early (< 70 days)       | 0         | 0.00                   | 0.69                |
|                                                    | Medium (70–90 days)     | 19        | 55.88                  |                     |
|                                                    | Late (> 90 days)        | 15        | 44.11                  |                     |
| Flower/fruit orientation                           | Drooping                | 8         | 23.53                  | 0.99                |
|                                                    | Semi- drooping          | 19        | 55.88                  |                     |
|                                                    | Erect                   | 7         | 20.59                  |                     |
| Fruit bearing habit                                | 1 (Solitary)            | 34        | 100                    | 0.00                |
|                                                    | 2–3                     | 0         | 0.00                   |                     |
|                                                    | > 3 (Cluster)           | 0         | 0.00                   |                     |
| Fruit colour (at mature unripe stage)              | White                   | 0         | 0.00                   | 0.35                |
|                                                    | Cream                   | 2         | 5.88                   |                     |
|                                                    | Green                   | 31        | 91.18                  |                     |
|                                                    | Purple                  | 1         | 2.94                   |                     |
| Intensity of fruit colour (at mature unripe stage) | Light                   | 5         | 14.71                  | 0.95                |
|                                                    | Medium                  | 9         | 26.47                  |                     |
|                                                    | Dark                    | 20        | 58.82                  |                     |
| Fruit length (cm)                                  | Short (< 3 cm)          | 0         | 0.00                   | 0.61                |
|                                                    | Medium (3.01-6 cm)      | 10        | 29.41                  |                     |
|                                                    | Long (> 6 cm)           | 24        | 70.59                  |                     |
| Fruit diameter (cm)                                | Narrow (< 3 cm)         | 0         | 0.00                   | 0.65                |
|                                                    | Medium (3.01-5 cm)      | 22        | 64.71                  |                     |
|                                                    | Broad (> 5 cm)          | 12        | 35.29                  |                     |
| Fruit shape in longitudinal section                | Oblate                  | 0         | 0.00                   | 1.01                |
|                                                    | Circular                | 0         | 0.00                   |                     |
|                                                    | Cordate                 | 0         | 0.00                   |                     |
|                                                    | Square                  | 19        | 55.88                  |                     |

| Trait                                   | State                 | Frequency | Relative frequency (%) | Diversity index (H) |
|-----------------------------------------|-----------------------|-----------|------------------------|---------------------|
|                                         | Rectangular           | 11        | 32.35                  |                     |
|                                         | Trapezoidal           | 3         | 8.82                   |                     |
|                                         | Moderately triangular | 1         | 2.94                   |                     |
|                                         | Narrowly triangular   | 0         | 0.00                   |                     |
|                                         | Horn shaped           | 0         | 0.00                   |                     |
|                                         | Others(specify)       | 0         | 0.00                   |                     |
| Fruit curvature                         | Absent                | 33        | 97.06                  | 0.13                |
|                                         | Present               | 1         | 2.94                   |                     |
| Fruit curvature intensity               | Low                   | 1         | 2.94                   | 0.10                |
|                                         | Medium                | 0         | 0.00                   |                     |
|                                         | High                  | 0         | 0.00                   |                     |
| Texture of fruit surface                | Smooth                | 32        | 94.11                  | 0.22                |
|                                         | Slightly rough        | 2         | 5.88                   |                     |
|                                         | Rough                 | 0         | 0.00                   |                     |
| Fruit colour (at ripe maturity)         | Yellow                | 4         | 11.76                  | 0.49                |
|                                         | Orange                | 1         | 2.94                   |                     |
|                                         | Red                   | 29        | 85.29                  |                     |
|                                         | Brown                 | 0         | 0                      |                     |
|                                         | Others (specify)      | 0         | 0                      |                     |
| Intensity of fruit colour (at maturity) | Light                 | 0         | 0.00                   | 0.00                |
|                                         | Medium                | 0         | 0.00                   |                     |
|                                         | Dark                  | 34        | 100                    |                     |
| Fruit glossiness                        | Weak                  | 0         | 0.00                   | 0.68                |
|                                         | Medium                | 14        | 41.18                  |                     |
|                                         | Strong                | 20        | 58.82                  |                     |
| Fruit shape at the base                 | Acute                 | 0         | 0.00                   | 0.13                |
|                                         | Round                 | 1         | 2.94                   |                     |
|                                         | Sunken                | 33        | 97.06                  |                     |
| Fruit shape of apex                     | Acute                 | 0         | 0.00                   | 0.22                |
|                                         | Blunt                 | 0         | 0.00                   |                     |
|                                         | Depressed             | 2         | 5.88                   |                     |
|                                         | Depressed & Acute     | 32        | 94.12                  |                     |
|                                         | Others (specify)      | 0         | 0                      |                     |
| number of lobes per fruit               | 2                     | 2         | 5.88                   | 0.93                |
|                                         | 2-3                   | 10        | 29.41                  |                     |
|                                         | 3                     | 1         | 2.94                   |                     |
|                                         | 3-4                   | 21        | 61.76                  |                     |
|                                         | > 4                   | 0         | 0.00                   |                     |
| Pericarp thickness(mm)                  | Very thin (< 1 mm)    | 0         | 0.00                   | 0.78                |
|                                         | Thin (1.01-2 mm)      | 0         | 0.00                   |                     |
|                                         | Medium (2.01-3 mm)    | 2         | 5.88                   |                     |
|                                         | Thick (3.01-4 mm)     | 9         | 23.53                  |                     |
|                                         | Verythick (> 4 mm)    | 23        | 70.59                  |                     |

| Trait                       | State                 | Frequency | Relative frequency (%) | Diversity index (H) |
|-----------------------------|-----------------------|-----------|------------------------|---------------------|
| fruit blossom end appendage | Absent                | 34        | 100                    | 0.00                |
|                             | Present               | 0         | 0.00                   |                     |
| Days to 50% fruit ripening  | Early (< 100 days)    | 9         | 26.47                  | 0.58                |
|                             | Medium (101–120 days) | 25        | 73.53                  |                     |
|                             | Late (> 120 days)     | 0         | 0.00                   |                     |
| 1000 seed weight (g)        | Low (< 4 g)           | 0         | 0.00                   | 0.61                |
|                             | Medium (4.01-6 g)     | 10        | 29.41                  |                     |
|                             | High (> 6 g)          | 24        | 70.59                  |                     |
| Seed colour                 | Light yellow          | 34        | 100                    | 0.00                |
|                             | Yellow                | 0         | 0.00                   |                     |
|                             | Orange yellow         | 0         |                        |                     |
|                             | Others (specify)      | 0         |                        |                     |
| Mean                        |                       |           |                        | 0.44                |
| Range                       |                       |           |                        | 1.01                |

## Mean performance of bell pepper genotypes

Significant genetic variability was indicated by the analysis of variance (ANOVA), which revealed statistically highly significant differences between the genotypes across all the traits under study (Table 3). Pooled data for 17 horticultural traits revealed UHF-CAP-108, UHF-CAP-119, IIHR- 131, UHF-CAP-106 and UHF-CAP-113 were the best genotypes as they were significantly superior than the better check variety i.e., Solan Bharpur for fruit yield per plant. They also took comparatively less days to achieve marketable maturity with desirable medium sized, blocky, dark green, glossy and 3–4 lobed fruit. Previous studies by Faizan et al. (2022) and Sood et al. (2023) also reported considerable variability.

| Table 3<br>Mean performance of different bell pepper genotypes for different horticultural traits (Pooled data of 2022–23 and 2023–24)                                                                                                                                                                                                                                            |       |       |         |         |         |         |         |                       |         |         |      |         |       |        |         |         |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---------|---------|---------|---------|---------|-----------------------|---------|---------|------|---------|-------|--------|---------|---------|
| Genotypes                                                                                                                                                                                                                                                                                                                                                                         | DFF   | DFP   | IL (cm) | PH (cm) | PS (cm) | LL (cm) | LW (cm) | LA (cm <sup>2</sup> ) | FL (cm) | FD (cm) | NLF  | PT (mm) | NFP   | FW (g) | FYP (g) | FYH (q) |
| UHF-CAP-101                                                                                                                                                                                                                                                                                                                                                                       | 38.67 | 69.33 | 9.19    | 55.38   | 46.02   | 9.53    | 4.73    | 31.37                 | 5.65    | 4.77    | 3.33 | 4.67    | 12.33 | 70.05  | 814.69  | 241     |
| UHF-CAP-102                                                                                                                                                                                                                                                                                                                                                                       | 37.00 | 69.00 | 9.35    | 59.28   | 46.91   | 10.28   | 4.77    | 33.93                 | 5.27    | 4.56    | 3.47 | 4.12    | 12.52 | 98.00  | 1046.40 | 310     |
| UHF-CAP-103                                                                                                                                                                                                                                                                                                                                                                       | 40.00 | 71.33 | 9.32    | 59.87   | 37.95   | 10.27   | 4.52    | 31.97                 | 5.15    | 4.93    | 3.07 | 5.20    | 14.33 | 78.87  | 1076.43 | 318     |
| UHF-CAP-104                                                                                                                                                                                                                                                                                                                                                                       | 38.33 | 70.00 | 11.29   | 60.43   | 43.69   | 9.17    | 4.35    | 27.52                 | 7.22    | 5.01    | 3.16 | 5.01    | 12.47 | 63.68  | 749.80  | 222     |
| UHF-CAP-105                                                                                                                                                                                                                                                                                                                                                                       | 42.00 | 77.67 | 11.12   | 61.15   | 42.87   | 7.92    | 4.52    | 24.69                 | 6.25    | 5.27    | 3.20 | 4.63    | 8.68  | 101.84 | 784.00  | 232     |
| UHF-CAP-106                                                                                                                                                                                                                                                                                                                                                                       | 38.00 | 69.67 | 10.70   | 58.18   | 45.04   | 10.78   | 4.89    | 36.52                 | 6.83    | 5.13    | 3.73 | 4.65    | 17.98 | 77.58  | 1302.78 | 386     |
| UHF-CAP-107                                                                                                                                                                                                                                                                                                                                                                       | 39.33 | 72.33 | 11.39   | 63.12   | 42.75   | 8.94    | 4.47    | 27.71                 | 7.71    | 5.16    | 3.07 | 5.52    | 8.72  | 71.73  | 511.10  | 151     |
| UHF-CAP-108                                                                                                                                                                                                                                                                                                                                                                       | 39.00 | 69.33 | 12.62   | 65.98   | 44.53   | 9.43    | 4.34    | 28.19                 | 6.18    | 4.82    | 3.53 | 4.69    | 18.09 | 78.06  | 1408.55 | 417     |
| UHF-CAP-109                                                                                                                                                                                                                                                                                                                                                                       | 39.67 | 73.00 | 8.26    | 55.48   | 42.16   | 10.77   | 5.65    | 42.05                 | 5.97    | 5.57    | 3.33 | 4.32    | 6.52  | 75.25  | 482.49  | 142     |
| UHF-CAP-110                                                                                                                                                                                                                                                                                                                                                                       | 37.33 | 66.00 | 9.60    | 53.04   | 35.86   | 8.93    | 3.86    | 23.85                 | 7.85    | 5.08    | 3.40 | 3.16    | 12.40 | 95.29  | 1116.67 | 330     |
| UHF-CAP-111                                                                                                                                                                                                                                                                                                                                                                       | 38.33 | 66.33 | 10.24   | 60.77   | 40.45   | 10.71   | 5.01    | 37.22                 | 6.75    | 4.51    | 2.60 | 3.31    | 6.73  | 68.91  | 396.68  | 117     |
| UHF-CAP-112                                                                                                                                                                                                                                                                                                                                                                       | 35.67 | 67.67 | 7.13    | 51.46   | 42.63   | 8.21    | 3.69    | 21.23                 | 6.39    | 4.26    | 3.20 | 4.16    | 13.08 | 65.18  | 817.69  | 242     |
| UHF-CAP-113                                                                                                                                                                                                                                                                                                                                                                       | 40.33 | 73.33 | 8.51    | 55.40   | 36.91   | 9.14    | 4.38    | 27.85                 | 6.09    | 5.35    | 3.60 | 4.14    | 18.64 | 72.36  | 1305.51 | 386     |
| UHF-CAP-114                                                                                                                                                                                                                                                                                                                                                                       | 40.00 | 73.33 | 6.97    | 46.69   | 50.91   | 11.13   | 4.75    | 36.42                 | 10.34   | 3.56    | 1.40 | 3.44    | 17.18 | 47.93  | 714.86  | 211     |
| UHF-CAP-115                                                                                                                                                                                                                                                                                                                                                                       | 39.00 | 70.00 | 8.41    | 55.41   | 46.59   | 9.12    | 4.16    | 26.33                 | 7.00    | 4.46    | 3.40 | 3.35    | 18.05 | 43.21  | 719.69  | 213     |
| UHF-CAP-116                                                                                                                                                                                                                                                                                                                                                                       | 40.33 | 75.33 | 9.16    | 58.61   | 47.46   | 9.03    | 4.22    | 26.36                 | 5.35    | 4.23    | 3.33 | 4.10    | 19.40 | 40.34  | 727.58  | 215     |
| UHF-CAP-117                                                                                                                                                                                                                                                                                                                                                                       | 40.67 | 75.33 | 11.45   | 62.04   | 45.17   | 8.30    | 3.95    | 22.65                 | 5.24    | 4.21    | 3.13 | 4.13    | 17.93 | 38.26  | 655.69  | 194     |
| UHF-CAP-118                                                                                                                                                                                                                                                                                                                                                                       | 42.33 | 75.33 | 7.45    | 52.54   | 45.76   | 9.18    | 4.02    | 25.50                 | 5.53    | 4.27    | 3.07 | 3.12    | 16.10 | 44.37  | 680.63  | 201     |
| UHF-CAP-119                                                                                                                                                                                                                                                                                                                                                                       | 38.33 | 70.33 | 12.09   | 65.59   | 46.93   | 10.02   | 5.05    | 35.07                 | 6.90    | 5.05    | 3.33 | 4.42    | 19.31 | 72.71  | 1372.58 | 406     |
| UHF-CAP-120                                                                                                                                                                                                                                                                                                                                                                       | 41.00 | 73.33 | 11.21   | 62.10   | 49.57   | 10.30   | 5.26    | 37.51                 | 6.23    | 4.36    | 2.60 | 3.51    | 18.27 | 59.77  | 992.56  | 294     |
| UHF-CAP-121                                                                                                                                                                                                                                                                                                                                                                       | 42.33 | 76.33 | 8.32    | 55.40   | 44.24   | 8.69    | 4.84    | 29.19                 | 6.66    | 4.72    | 3.00 | 4.11    | 11.33 | 40.62  | 410.55  | 121     |
| UHF-CAP-122                                                                                                                                                                                                                                                                                                                                                                       | 38.67 | 72.67 | 8.62    | 56.91   | 42.50   | 7.74    | 4.06    | 21.81                 | 6.58    | 3.58    | 2.07 | 2.92    | 13.60 | 36.36  | 462.41  | 137     |
| UHF-CAP-123                                                                                                                                                                                                                                                                                                                                                                       | 41.33 | 75.33 | 9.32    | 60.29   | 35.82   | 8.71    | 4.19    | 25.27                 | 5.09    | 4.38    | 2.40 | 5.19    | 12.53 | 67.38  | 800.45  | 237     |
| UHF-CAP-124                                                                                                                                                                                                                                                                                                                                                                       | 39.33 | 68.67 | 9.70    | 62.53   | 42.18   | 9.17    | 4.77    | 30.21                 | 8.02    | 4.02    | 2.20 | 3.02    | 11.74 | 37.79  | 467.38  | 138     |
| UHF-CAP-125                                                                                                                                                                                                                                                                                                                                                                       | 37.67 | 69.67 | 8.21    | 55.46   | 42.94   | 10.60   | 4.89    | 35.80                 | 7.51    | 4.39    | 2.13 | 3.83    | 8.42  | 44.73  | 338.34  | 100     |
| UHF-CAP-126                                                                                                                                                                                                                                                                                                                                                                       | 43.00 | 75.33 | 7.73    | 50.22   | 38.06   | 9.49    | 5.14    | 33.70                 | 8.09    | 5.37    | 2.69 | 4.10    | 4.97  | 86.92  | 392.15  | 116     |
| DFF, Days to 50% flowering; DFP, Days to first picking; IL, internodal length; PH, Plant height; PS, Plant spread; LL, Leaf length; LW, Leaf width; LA, Leaf area; FFD, Fruit diameter; NLF, Number of lobes per fruit; PT, Pericarp thickness; NFP, Number of fruits per plant; FW, Fruit weight; FYP, Fruit yield per plant; FYH, Fruit yield per ha; TSW, Thousand seed weight |       |       |         |         |         |         |         |                       |         |         |      |         |       |        |         |         |

| Genotypes                                                                                                                                                                                                                                                                                                                                                                      | DFF   | DFP   | IL (cm) | PH (cm) | PS (cm) | LL (cm) | LW (cm) | LA (cm <sup>2</sup> ) | FL (cm) | FD (cm) | NLF  | PT (mm) | NFP   | FW (g) | FYP (g) | FYT (q) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---------|---------|---------|---------|---------|-----------------------|---------|---------|------|---------|-------|--------|---------|---------|
| UHF-CAP-127                                                                                                                                                                                                                                                                                                                                                                    | 43.33 | 75.00 | 8.24    | 52.52   | 35.02   | 8.23    | 3.92    | 22.32                 | 6.48    | 4.18    | 3.20 | 4.10    | 10.78 | 43.16  | 424.34  | 125     |
| UHF-CAP-128                                                                                                                                                                                                                                                                                                                                                                    | 43.67 | 75.00 | 9.21    | 57.13   | 38.67   | 9.03    | 4.23    | 26.24                 | 9.03    | 3.66    | 1.76 | 4.05    | 13.70 | 52.17  | 672.08  | 199     |
| IIHR-131                                                                                                                                                                                                                                                                                                                                                                       | 38.67 | 71.67 | 10.34   | 63.71   | 43.27   | 11.44   | 7.08    | 56.00                 | 5.60    | 4.41    | 3.80 | 6.05    | 14.49 | 98.04  | 1364.07 | 404     |
| IIHR-132                                                                                                                                                                                                                                                                                                                                                                       | 39.33 | 71.33 | 8.27    | 54.23   | 39.69   | 9.90    | 5.23    | 35.84                 | 6.97    | 5.85    | 3.20 | 4.18    | 11.73 | 61.59  | 624.35  | 184     |
| IIHR-133                                                                                                                                                                                                                                                                                                                                                                       | 41.33 | 75.33 | 7.00    | 44.57   | 25.66   | 6.57    | 2.23    | 10.19                 | 6.95    | 5.56    | 2.27 | 3.10    | 6.70  | 65.07  | 425.24  | 125     |
| IIHR-134                                                                                                                                                                                                                                                                                                                                                                       | 40.67 | 76.67 | 7.03    | 43.07   | 29.01   | 8.17    | 3.06    | 17.38                 | 6.39    | 4.72    | 2.40 | 2.84    | 8.13  | 58.39  | 451.60  | 133     |
| Solan Bharpur (check)                                                                                                                                                                                                                                                                                                                                                          | 41.67 | 76.33 | 8.21    | 52.48   | 45.06   | 8.66    | 4.33    | 26.25                 | 5.54    | 4.75    | 2.81 | 4.73    | 18.07 | 55.91  | 1236.29 | 366     |
| California Wonder (check)                                                                                                                                                                                                                                                                                                                                                      | 43.00 | 77.67 | 11.41   | 66.19   | 56.87   | 11.23   | 6.22    | 48.47                 | 7.81    | 5.33    | 3.51 | 5.21    | 12.58 | 96.83  | 1129.88 | 334     |
| Mean                                                                                                                                                                                                                                                                                                                                                                           | 39.98 | 72.51 | 9.33    | 56.98   | 42.33   | 9.38    | 4.55    | 30.08                 | 6.67    | 4.69    | 2.95 | 4.15    | 13.16 | 65.04  | 790.46  | 234     |
| Genotypes significantly superior than check                                                                                                                                                                                                                                                                                                                                    | 21    | 23    | 06      | 0       | 0       | 0       | 01      | 01                    | 02      | 0       | 0    | 02      | 02    | 0      | 05      | 05      |
| SE±(m)                                                                                                                                                                                                                                                                                                                                                                         | 0.47  | 0.36  | 0.07    | 1.40    | 1.41    | 0.38    | 0.27    | 2.20                  | 0.27    | 0.21    | 0.21 | 0.10    | 0.35  | 2.07   | 19.40   | 0.2     |
| CD (p = 0.05)                                                                                                                                                                                                                                                                                                                                                                  | 1.33  | 1.02  | 0.19    | 3.97    | 3.98    | 1.08    | 0.76    | 6.24                  | 0.76    | 0.59    | 0.60 | 0.29    | 0.98  | 5.87   | 54.91   | 0.5     |
| DFF, Days to 50% flowering; DFP, Days to first picking; IL, internodal length; PH, Plant height; PS, Plant spread; LL, Leaf length; LW, Leaf width; LA, Leaf area; F Fruit diameter; NLF, Number of lobes per fruit; PT, Pericarp thickness; NFP, Number of fruits per plant; FW, Fruit weight; FYP, Fruit yield per plant; FYH, Fruit yield per ha; TSW, Thousand seed weight |       |       |         |         |         |         |         |                       |         |         |      |         |       |        |         |         |

## Cluster analysis

All the 34 genotypes of bell pepper were grouped into 5 clusters based on the Mahalanobis  $D^2$  values (Fig. 1) in which cluster 2 contained maximum number of genotypes (10) viz., UHF-CAP-114, UHF-CAP-115, UHF-CAP-116, UHF-CAP-117, UHF-CAP-118, UHF-CAP-121, UHF-CAP-122, UHF-CAP-124, UHF-CAP-127, UHF-CAP-128 followed by cluster 5 with 9 genotypes i.e., UHF-CAP-105, UHF-CAP-107, UHF-CAP-109, UHF-CAP-110, UHF-CAP-111, UHF-CAP-112, UHF-CAP-125, UHF-CAP-126 and IIHR-132. Cluster 4 contained 8 genotypes; UHF-CAP-101, UHF-CAP-102, UHF-CAP-103, UHF-CAP-104, UHF-CAP-113, UHF-CAP-120, UHF-CAP-123 and Solan Bharpur. Cluster 3 with 5 genotypes viz., UHF-CAP-106, UHF-CAP-108, UHF-CAP-119, IIHR-131 and California Wonder characterized by the highest fruit yield per plant (g) as shown in Table 4. Cluster 1 contained minimum number of genotypes (IIHR-133 and IIHR-134). Hence, the genetically homogeneous genotypes likely to fall in the same cluster and the most diverse genotypes in different clusters. Similar clustering patterns of bell pepper genotypes were also reported by Sharma et al. (2017) and Sood et al. (2023). The maximum inter cluster distance was between cluster III and cluster V (9.74) which shows maximum genetic divergence between the genotypes of these clusters (Table 5). Number of seeds per fruit contributed maximum (9.27%) towards genetic divergence, followed by thousand seed weight (8.73%), days to 50% flowering (8.38%), plant spread (8.20%), fruit weight (6.77%), days to first picking and number of fruits per plant (6.42%), fruit yield per plant (6.24%), internodal length and pericarp thickness (6.06%), fruit length (5.88%), fruit diameter and number of lobes per fruit (4.81%), plant height (3.39%), leaf length (3.21%) while, leaf area (2.85%) and leaf width (2.50%) contributed minimum towards genetic divergence (Table 6 and Fig. 2). Similar observations were recorded by Sood et al. (2023), Anuradha et al. (2024) and Arti et al. (2025).

Table 4  
Cluster means for different traits among thirty-four bell pepper genotypes

| Traits                       | Clusters |        |         |        |        |
|------------------------------|----------|--------|---------|--------|--------|
|                              | I        | II     | III     | IV     | V      |
| Days to 50% flowering        | 39.79    | 39.14  | 39.40   | 40.97  | 41.00  |
| Days to first picking        | 72.25    | 71.04  | 71.73   | 73.69  | 76.00  |
| Internodal length (cm)       | 9.55     | 9.11   | 11.43   | 8.75   | 7.01   |
| Plant height (cm)            | 58.15    | 56.10  | 63.93   | 55.98  | 43.82  |
| Plant spread (cm)            | 42.74    | 40.82  | 47.33   | 43.85  | 27.34  |
| Leaf length (cm)             | 9.56     | 9.49   | 10.58   | 8.96   | 7.37   |
| Leaf width (cm)              | 4.56     | 4.72   | 5.52    | 4.29   | 2.64   |
| Leaf area (cm <sup>2</sup> ) | 30.21    | 31.34  | 40.85   | 26.70  | 13.78  |
| Fruit length (cm)            | 5.78     | 7.05   | 6.66    | 7.02   | 6.67   |
| Fruit diameter (cm)          | 4.76     | 5.05   | 4.95    | 4.09   | 5.14   |
| Number of lobes per fruit    | 3.05     | 2.98   | 3.58    | 2.66   | 2.33   |
| Pericarp thickness (mm)      | 4.57     | 4.13   | 5.00    | 3.63   | 2.97   |
| Number of fruits per plant   | 14.89    | 9.03   | 16.49   | 14.98  | 7.42   |
| Fruit weight (g)             | 70.75    | 74.60  | 84.64   | 42.42  | 61.73  |
| Number of seeds per fruit    | 244.05   | 190.72 | 173.29  | 193.85 | 192.92 |
| Thousand seed weight (g)     | 5.50     | 6.27   | 6.01    | 6.56   | 6.75   |
| Fruit yield per plant (g)    | 1002.76  | 607.05 | 1315.57 | 593.52 | 438.42 |

Table 5  
Average intra and inter cluster distance

| Cluster | I           | II          | III         | IV          | V           |
|---------|-------------|-------------|-------------|-------------|-------------|
| I       | <b>4.11</b> |             |             |             |             |
| II      | 3.07        | <b>5.27</b> |             |             |             |
| III     | 3.76        | 4.83        | <b>4.58</b> |             |             |
| IV      | 3.69        | 3.30        | 5.95        | <b>4.54</b> |             |
| V       | 6.95        | 5.76        | 9.74        | 5.57        | <b>3.89</b> |

Table 6  
Relative contribution (%) of individual traits to the genetic divergence  
among bell pepper genotypes

| Source                       | Times ranked 1st | Contribution (%) |
|------------------------------|------------------|------------------|
| Days to 50% flowering        | 47               | 8.38             |
| Days to first picking        | 36               | 6.42             |
| Internodal length (cm)       | 34               | 6.06             |
| Plant height (cm)            | 19               | 3.39             |
| Plant spread (cm)            | 46               | 8.20             |
| Leaf length (cm)             | 18               | 3.21             |
| Leaf width (cm)              | 14               | 2.50             |
| Leaf area (cm <sup>2</sup> ) | 16               | 2.85             |
| Fruit length (cm)            | 33               | 5.88             |
| Fruit diameter (cm)          | 27               | 4.81             |
| Number of lobes per fruit    | 27               | 4.81             |
| Pericarp thickness (mm)      | 34               | 6.06             |
| Number of fruits per plant   | 36               | 6.42             |
| Fruit weight (g)             | 38               | 6.77             |
| Number of seeds per fruit    | 52               | 9.27             |
| Thousand seed weight (g)     | 49               | 8.73             |
| Fruit yield per plant (g)    | 35               | 6.24             |

## Principal component analysis

Principal component analysis (PCA) revealed six statistically significant principal components, which together accounted for 83.08% of the total observed variation. The first principal component (PC1) was the most important, explaining 33.63% of the total variance and was predominantly associated with thousand seed weight. The remaining components, namely PC2, PC3, PC4, PC5, and PC6, were primarily governed by number of lobes per fruit, fruit diameter, fruit weight, internodal length and fruit length, contributing 13.12%, 11.93%, 10.72%, 7.35% and 6.33% of the total variance, respectively (Table 7) as explained by Sood et al. (2023), Anuradha et al. (2024) and Arti et al. (2025). The PC1 and PC2 biplot provided a comprehensive visualization of the relative importance of agro-morphological traits and genotypic diversity in explaining phenotypic variation and delineating species-level associations (Fig. 3).

Table 7  
Percent variation by six significant principal components of different traits in bell pepper genotypes.

| Traits                       | PC1    | PC2    | PC3    | PC4    | PC5    | PC6    |
|------------------------------|--------|--------|--------|--------|--------|--------|
| Days to 50% flowering        | 0.126  | -0.072 | 0.292  | -0.519 | -0.236 | 0.005  |
| Days to first picking        | 0.119  | 0.009  | 0.282  | -0.551 | -0.258 | -0.060 |
| Internodal length (cm)       | -0.282 | 0.028  | 0.003  | -0.160 | 0.438  | -0.113 |
| Plant height (cm)            | -0.303 | -0.071 | -0.025 | -0.169 | 0.358  | -0.269 |
| Plant spread (cm)            | -0.245 | -0.294 | -0.213 | -0.173 | -0.072 | -0.159 |
| Leaf length (cm)             | -0.278 | -0.369 | 0.016  | 0.167  | -0.218 | 0.079  |
| Leaf width (cm)              | -0.300 | -0.352 | 0.169  | 0.017  | -0.136 | -0.090 |
| Leaf area (cm <sup>2</sup> ) | -0.301 | -0.363 | 0.139  | 0.085  | -0.187 | -0.013 |
| Fruit length (cm)            | 0.095  | -0.401 | 0.044  | 0.084  | 0.238  | 0.496  |
| Fruit diameter (cm)          | -0.107 | 0.276  | 0.454  | 0.193  | -0.011 | -0.027 |
| Number of lobes per fruit    | -0.270 | 0.324  | 0.095  | 0.048  | -0.059 | -0.129 |
| Pericarp thickness (mm)      | -0.275 | 0.067  | 0.268  | -0.164 | 0.068  | -0.069 |
| Number of fruits per plant   | -0.172 | 0.097  | -0.478 | -0.321 | -0.065 | 0.124  |
| Fruit weight (g)             | -0.238 | 0.163  | 0.352  | 0.196  | -0.051 | 0.301  |
| Fruit yield per plant (g)    | -0.318 | 0.232  | -0.146 | -0.111 | -0.079 | 0.371  |
| Fruit yield per ha (q)       | -0.318 | 0.232  | -0.146 | -0.111 | -0.079 | 0.371  |
| Number of seeds per fruit    | -0.026 | 0.082  | -0.212 | 0.191  | -0.603 | -0.116 |
| Thousand seed weight (g)     | 0.142  | -0.113 | 0.103  | -0.172 | 0.046  | 0.456  |
| Eigen value                  | 2.460  | 1.536  | 1.465  | 1.389  | 1.149  | 1.067  |
| Variation (%)                | 33.63  | 13.12  | 11.93  | 10.72  | 7.34   | 6.33   |
| Cumulative Variation (%)     | 33.63  | 46.75  | 58.68  | 69.41  | 76.75  | 83.08  |

## CONCLUSION

The study highlights the significant variability among 34 bell pepper genotypes based on morpho-agronomic traits under study with genotypes UHF-CAP-108, UHF-CAP-119, IIHR- 131, UHF-CAP-106 and UHF-CAP-113 exhibiting high fruit yield per plant which was significantly superior than the better check variety *i.e.*, Solan Bharpur. Principal Component Analysis (PCA) has identified key traits including thousand seed weight, number of lobes per fruit, fruit diameter, fruit weight, internodal length and fruit length which directly affect fruit quality and yield. Hence, these traits play an essential role for choosing desirable genotypes in future breeding programs.

## Declarations

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### AUTHOR CONTRIBUTIONS

Conceptualization: GK, DKM; Data: GK, DKM; Formal analysis: GK, DKM; Methodology: GK, AS, TKM; Resources: DKM; Writing & reviewing of manuscript: GK, DKM, AS, ND, TKM.

### AVAILABILITY OF DATA AND MATERIAL

The data supporting this study are available from the authors upon reasonable request.

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### COMPETING INTERESTS

The authors declare that they have no conflicts of interest or competing interests related to this research.

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## Figures

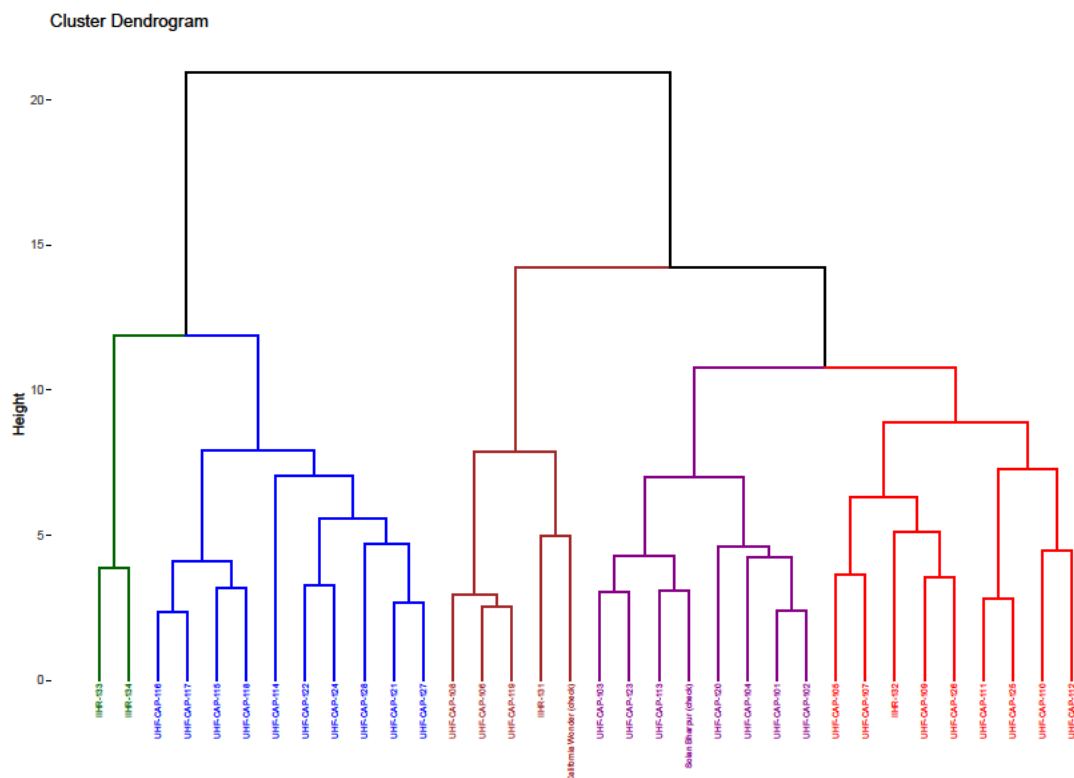


Figure 1

Dendrogram showing grouping of 34 bell pepper genotypes into 5 clusters based on Mahalanobis D2 analysis using Ward's method.

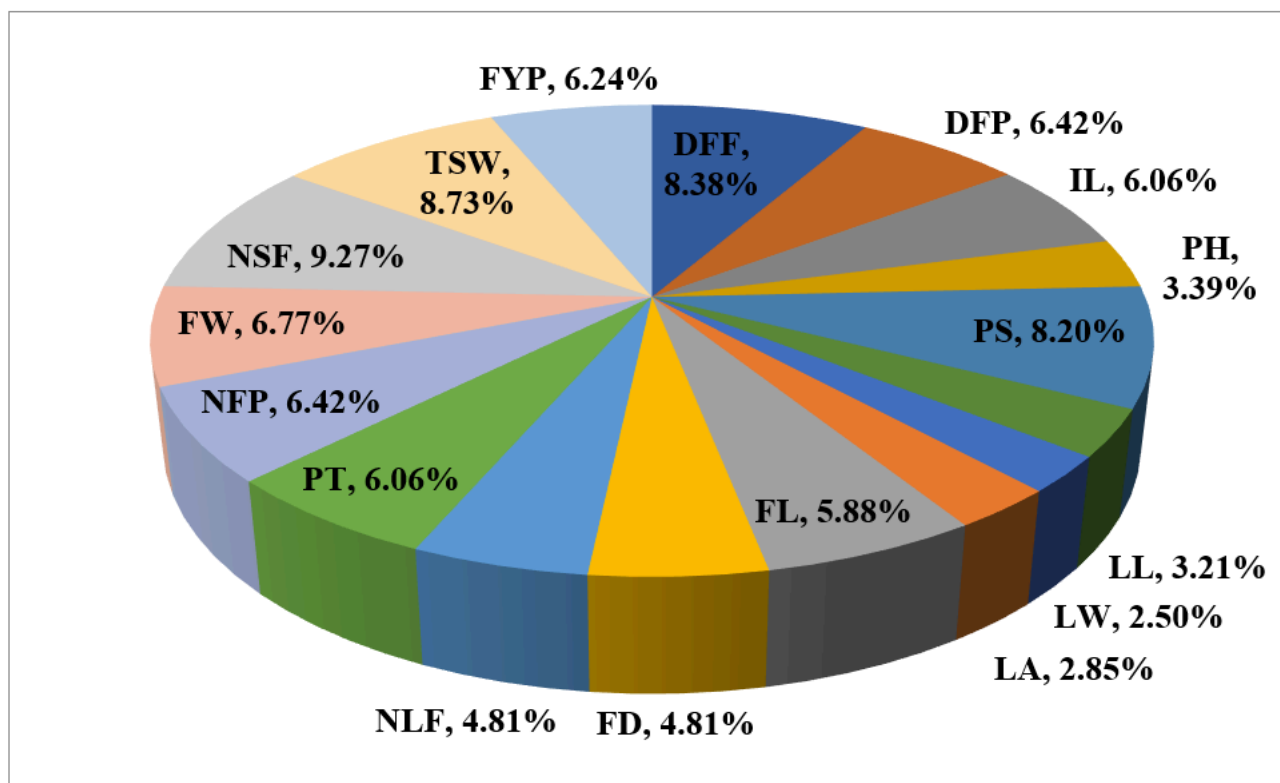
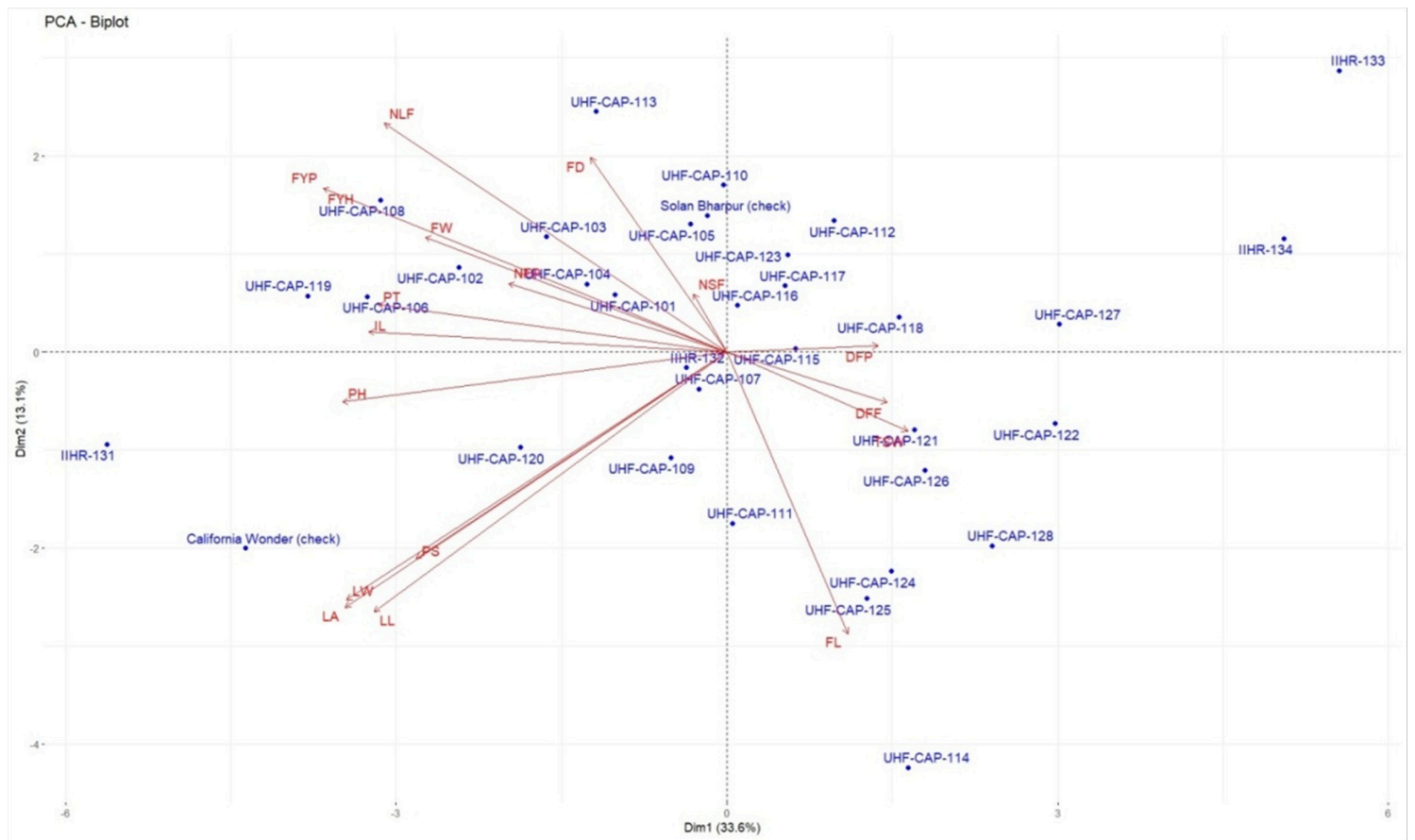


Figure 2

Relative contribution (%) of individual traits to the genetic divergence among bell pepper genotypes.



**Figure 3**

Principal component analysis biplot for 34 bell pepper genotypes; where; DFF, Days to 50% flowering; DFP, Days to first picking; IL, internodal length; PH, Plant height; PS, Plant spread; LL, Leaf length; LW, Leaf width; LA, Leaf area; FL, Fruit length; FD, Fruit diameter; NLF, Number of lobes per fruit; PT, Pericarp thickness; NFP, Number of fruits per plant; FW, Fruit weight; FYP, Fruit yield per plant; FYH, Fruit yield per ha; NSF, Number of seeds per fruit; TSW, Thousand seed weight