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RESEARCH ARTICLE

Morphological variability for flowering, bunch and berry traits in grapes (*Vitis vinifera* L.) germplasm under subtropical conditions

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Abstract

Grapevine (*Vitis vinifera* L.) is one of the world's most important fruit crops, growing widely in the temperate zone; however, Indian viticulture is unique and predominantly cultivated in tropical and sub-tropical climatic conditions. In the present study, 48 grape genotypes, including newly developed hybrids, were evaluated for key morphological and pomological parameters related to flowering, bunch and berry traits under Indian subtropical conditions at ICAR- Indian Agricultural Research Institute (IARI), New Delhi during 2021–2022. Results revealed a large genetic variability for the morpho-pomological parameters. It was found that the genotypes Hyb_16_2A_R1P2, Hyb_16_2A_R1P19, Hyb_16_2A_R3P18, Hyb_16_2A_R4P3, Julesky Muscat and Pearl of Csaba were early-flowering and early-maturing, making them attractive for the cultivation and breeding of grapes for subtropical climates. Among the genotypes under examination, bunch weight, bunch width, bunch length, berry weight, berry length and berry width varied from 54.07–477.35 g, 6.82–14.12 cm, 8.07–25.57 cm, 0.72–5.60 g, 9.96–18.73 mm and 9.83–17.69 mm respectively. Over 70 % of the genotypes under study had spherical berries, while 19 genotypes (39.58 %) had no seeds. PCA indicated that berry weight, berry size, bunch weight and bunch length were the main characteristics controlling variability in the genotypes under study. The correlation analysis indicated 3 clusters based on the genetic relatedness and the association between the studied morpho-pomological features. This comprehensive categorisation provides a strategic structure for selecting genetically superior and diverse parent material to produce higher-quality, high-yielding cultivars appropriate for subtropical climates.

Keywords: berry and bunch traits; flowering; genetic diversity; grape genotypes; sub-tropical climate

Introduction

Grape (*Vitis vinifera* L.) is one of the most important fruit crops, originating from the Near East or Mediterranean region and widely cultivated across the temperate regions of the world. However, Indian viticulture is unique because it mainly grows in sub-tropical and tropical climatic conditions (1, 2). In India, most of the grape cultivation is concentrated in tropical areas, where management practices like double pruning help assure crop production during February–March (3, 4). Single-pruning and single-harvesting in June are common practices in the North Indian states, where subtropical grape production is practiced (5). The subtropical climate, which is characterised by a short growing season for berry development with high summer and distinct winter temperatures, presents unique challenges for subtropical grape production (6, 7). As a result, genotypes and cultivars often grown in tropical climates are unsuitable for subtropical climates. To expand the crop's acreage and yield, better genotypes that can be grown in the subtropical climate of North India must be developed and identified. A few cultivars have already been developed and suggested for the subtropical North Indian climate; still, it is necessary for breeding new, improved cultivars with better berry quality for the subtropical climate. Hybridisation has continued to be one of the most significant breeding techniques for grapevines despite inherent limitations in the breeding of perennial fruit crops. Under the breeding programme at ICAR- Indian Agricultural Research Institute (IARI), New Delhi, new grapevine hybrids have been developed using diverse parental combinations. The newly obtained hybrid progenies need to be screened to identify superior genotypes and pre-breeding material.

Grape is a major fruit crop with substantial nutritional and commercial significance. The identification of superior cultivars for breeding and cultivation is hampered in sub-tropical regions by the lack of thorough characterisation of local genotypes. Berry size, shape, colour, bunch features, flowering and harvesting time are examples of morphological and pomological properties that offer vital information for genotype identification, selection and improvement (8). Additionally, this kind of categorisation supports the selection of cultivars appropriate for sub-tropical conditions like early flowering and early maturing cultivars, coloured seedless and loose bunch with good berry size (9–11). Berry traits including size, shape and colour constitute key criteria for selection in grape breeding programmes. To distinguish between genotypes and identify superior varieties for sub-tropical conditions, breeding and conservation, phenotyping techniques were used in this work to thoroughly assess the grape germplasm (12).

These techniques include evaluating the flowering time and harvesting duration, bunch characteristics, fruit colour and form (13). Assessment of genetic variability facilitates the identification of key traits for developing and releasing superior genotypes (14–17). Compared with conventional grape-growing locales i.e., temperate regions, subtropical conditions often cause certain features like flowering time, berry development, harvesting and yield. Flowering, bunch and berry characteristics must be thoroughly assessed to find stable and superior genotypes for sub-tropical conditions and future crop improvement. The current study was conducted to determine the degree of phenotypic variability in flowering, bunch and berry traits across a varied panel of diverse grape genotypes grown in subtropical India. The results are intended to assist early flowering and early maturing cultivars, superior bunch traits like compactness, weight and dimension of the bunch and berry traits like colour, seedlessness, shape and size, which offers a scientific foundation for choosing prospective parental lines for breeding for early flowering, harvesting, better yield and quality of berry.

Materials and Methods

Experimental site

The experiment was conducted at ICAR–IARI, New Delhi, situated at latitude of 28.40° N, longitude of 77.10° E and an elevation of 228.16 m above mean sea level. The location is in the Trans-Gangetic Plains agroclimatic zone and has a semi-arid subtropical climate. Winters are frigid, with minimum temperatures between 2.2 °C and 7.4 °C in December and January, while summers are scorching, with maximum temperatures hovering between 36.8 °C and 41.1 °C in May and June. May had the greatest monthly average temperature (39.8 °C) throughout the studied years (2020–2022), while December had the lowest (4.8 °C) with the onset of monsoons in May and extends till October with average annual rainfall of around 770 mm.

Plant material

In the present study, 48 grape genotypes (Table 1), including released cultivars and new hybrids, were evaluated for two growing seasons (2021 and 2022). These genotypes were growing at the experimental farm (28.40° N, 77.10° E; 228 m above mean sea level) of the Division of Fruits and Horticultural Technology, ICAR-IARI, New Delhi. The evaluated genotypes were uniform in age and trained on the Kniffin system. The standard agronomic practices recommended for grape cultivation under subtropical conditions were followed throughout the study. The pruning was done in mid-January during the dormant stage and irrigation was given in weekly intervals and timely nutrients were applied along with micronutrient spray during berry development stage.

Morphological and pomological parameters

The selected vine genotypes were evaluated for various morphological and pomological parameters according to the guidelines provided in the IPGRI *Vitis* Descriptors (18). All the grape vines were pruned on the same calendar date. The number of days taken for the panicle to emerge from the date of pruning was considered for Days to panicle emergence (DPE). Days to full bloom were calculated as the number of days when 50 % of flower clusters on tagged shoots reached full bloom (flowers fully open) from the date of pruning. Days to harvest (DH) were assessed from the days of pruning until berries reached the harvestable stage, identified by optimum total soluble solids (TSS) and colour (18).

Table 1. The list of grape genotypes used in the present study

Sl. No	Genotypes	Sl. No	Genotypes
1	Hyb 16/2A R1P2	25	Perlette (Per)
2	Hyb 16/2A R1P7	26	Hur
3	Hyb 16/2A R1P9	27	Bharath Early (BE)
4	Hyb 16/2A R1P13	28	Anab-e-Shahi (AS)
5	Hyb 16/2A R1P14	29	Pusa Urvashi (PU)
6	Hyb 16/2A R1P15	30	Black Prince (BP)
7	Hyb 16/2A R1P18	31	Julesky Muscat (JM)
8	Hyb 16/2A R1P19	32	Black Muscat (BM)
9	Hyb 16/2A R1P20	33	Pusa Aditi (PA)
10	Hyb 16/2A R2P11	34	Pusa Seedless (PS)
11	Hyb 16/2A R2P12	35	Pusa Trishar (PT)
12	Hyb 16/2A R2P16	36	Beauty Seedless (BS)
13	Hyb 16/2A R3P1	37	Centennial Seedless (CS)
14	Hyb 16/2A R3P2	38	Cardinal (Car)
15	Hyb 16/2A R3P3	39	Pusa Navrang (PN)
16	Hyb 16/2A R3P10	40	Pearl of Csaba (POC)
17	Hyb 16/2A R3P18	41	Banqui Abyad (BA)
18	Hyb 16/2A R4P3	42	ER R1P16
19	Hyb 16/2A R4P7	43	Flame Seedless (FS)
20	Hyb 16/2A R4P9	44	Pusa Purple Seedless (PPS)
21	Hyb 16/2A R4P10	45	Punjab Purple (PP)
22	Hyb 16/2A R4P13	46	*Vitis parviflora* (VP)
23	Hyb 16/2A R5P8	47	Pusa Swarnika (P.Swa)
24	Hyb 16/2A R5P9	48	Hyb 72-151

The bunch parameters were taken as the average of 5 bunches for each replication and the number of replications were three. The bunch size parameters were measured with a digital vernier calliper (Model 500-196, Mitutoyo South Asia Pvt. Ltd., New Delhi) and the weight parameters were measured with a digital weighing balance (CTG 3101 Precision balance, Citizen Scale Pvt. Ltd., India). Bunch density and bunch peduncle length were measured on representative clusters following the IPGRI *Vitis* Descriptors (18).

Berry weight, length and width were measured from 10 mature berries per replication at the time of harvest. Berry shape (1-oblong, 2- narrow elliptic, 3- elliptic, 4- round, 5- oblate, 6- ovate, 7-obtuse-ovate, 8- obovate, 9-arched) and berry size (1-very small, 3-small, 5- medium, 7-large, 9- very large) were described as per IPGRI *Vitis* Descriptors (18). Furthermore, the presence of seeds was recorded based on the presence and absence of seed (present-1, absent-0) and the berry skin colour was recorded as 1-green-yellow, 2-rose, 3-red, 4-red grey, 5-dark red-violet, 6-blue-black) (18).

Statistical analyses

Significant differences among grape genotypes in morphological traits were assessed using a one-way analysis of variance (ANOVA) with the STAR software. Mean separation was performed using Fisher's least significant difference (LSD) test at $p \leq 0.05$. Pearson's correlation coefficients were calculated to examine associations among traits using R Software (R Studio Ver. 4.3.1). Principal component analysis (PCA) was conducted to explore the underlying structure of variability and relationships among cultivars. Hierarchical agglomerative clustering (HAC) was applied to group the studied grape genotypes based on trait similarity. Clustering was performed using the unweighted pair group method with arithmetic mean (UPGMA) linkage method based on the computed dissimilarity matrix.

Results

Morphological parameters

A significant difference was observed among the evaluated 48 grape genotypes for DPE, days to full bloom and days to harvest (DH), indicating strong genotypic influence on phenology (Table 2, 3 & 4). Days to panicle emergence showed the narrowest variation (CV = 0.46 %), with early panicle emergence (59.50 days) in Hyb_16_2A_R1P2, Hyb_16_2A_R1P19, Hyb_16_2A_R3P18 and Hyb_16_2A_R4P3 to delayed panicle emergence (73.50 days) in *Vitis Parviflora* Roxb. *with* the mean value (64.46 days) and low variability (SD = 3.41) was recorded. Julesky Muscat had the earliest 50 % bloom (71.50 days), followed by Pearl of Csaba (72.50 days) and Hyb_16_2A_R1P7, Hyb_16_2A_R5P9 (73.00 days), whereas *V. parviflora* took longest time to full bloom (87.50 days), followed by Hyb_16_2A_R1P14 (83.50 days). The range was 71.50 to 87.50 days, indicating significant differences in floral phenology between the genotypes.

The earliest harvest was observed in Julesky Muscat (136.50 days), followed by Pearl of Csaba (135.50 days) and Bharath Early (139.50 days). The last harvest was recorded in *V. parviflora* (173.00 days), making it the most delayed genotype in terms of crop duration, followed by Hyb_16_2A_R5P9 (167.50 days) and Hyb_16_2A_R5P8 (164.50 days). Most hybrids matured in 145–160 days**,** representing mid-season categories. The maturity period across genotypes ranged from 135.50 to 173.00 days, indicating a wide spectrum of early, mid and late-maturing groups within the evaluated population. Days to harvest (DH) had a mean of 151.43 days and moderate variability (SD = 7.99).

For all phenological traits, the pooled ANOVA across 2 years (2021 and 2022) revealed highly significant differences among grape genotypes. Although the effect of year was not substantial for DFB, the significant genotype × year interactions observed for DPE, DFB and DH ($p < 0.01$) indicate that phenological expression is highly sensitive to environmental fluctuations typical of subtropical regions.

Table 2. Analysis of variance (ANOVA) of morphological and pomological traits of grape genotypes

Pooled data (mean data of 2021 and 2022)										
Source	***df***	**DPE**	**DFB**	**DH**	**Bunch weight (g)**	**Bunch length (cm)**	**Bunch width (cm)**	**Berry weight (g)**	**Berry width (mm)**	**Berry length (mm)**
Year	1	140.28*	58.68	1309.01**	38.03	15.28	9.61*	0.03	0.11	0.03
Rep within Year	4	7.59	8.97	47.21	2101.74	8.05	0.80	0.08	0.82	1.55
Genotypes	47	63.72*	56.26**	384.01**	60782.37**	98.19**	22.26**	10.24**	17.29**	27.46**
Year: Genotypes	47	5.24**	6.73**	32.77**	14.28	0.13	0.01	0.00	0.00	0.00
Pooled Error	188	1.82	2.35	11.18	1205.19	1.14	0.49	0.11	0.37	0.35
Total	287									

*Significant with *p* value > 0.01; **Highly significant with *p* value < 0.01; Not significant with *p* value > 0.05

DPE-Days to panicle emergence, DFB- Days to full bloom, DH- Days to harvest.

Table 3. Descriptive statistics of morphological and pomological traits of the studied grape genotypes

Parameter (Pooled data)	**Days to panicle emergence**	**Days to full bloom (50 %)**	**Days to harvest**	**Bunch weight (g)**	**Bunch length (cm)**	**Bunch width (cm)**	**Berry weight (g)**	**Berry width (mm)**	**Berry length (mm)**
Mean	64.46	112.90	151.43	148.31	14.86	9.96	2.62	13.48	14.16
SE	0.49	6.19	1.15	12.45	0.58	0.28	0.19	0.25	0.31
Median	64.50	94.20	151.00	112.40	13.98	10.13	2.51	13.55	14.04
SD	3.41	42.87	7.99	86.27	4.05	1.93	1.31	1.70	2.14
Var	11.62	1837.76	63.84	7442.74	16.37	3.71	1.71	2.88	4.58
Kurtosis	-0.31	0.87	0.06	0.92	0.58	-0.74	-0.27	0.09	-0.40
Skewness	0.45	1.24	0.29	1.28	0.78	0.29	0.80	0.33	0.27
Range	14.00	181.91	37.50	362.81	17.50	7.30	4.88	7.86	8.77
Min	59.50	59.67	135.50	46.34	8.07	6.82	0.72	9.83	9.96
Max	73.50	241.58	173.00	409.16	25.57	14.12	5.60	17.69	18.73

Table 4. Morphological and pomological variability of the studied grape genotypes

	Genotypes	Days to panicle emergence	Days to full bloom	Days to harvest	Bunch weight (g)	Bunch width (cm)	Bunch length (cm)	Berry weight (g)	Berry width (mm)	Berry length (mm)
1	Hyb_16/2A_R1P2	59.50^{r}	76.50^{klm}	147.50^{v}	87.42^{qrstuv}	8.50^{n}	16.08^{hijk}	1.09^{wx}	11.63^{tuvw}	11.84^{xy}
2	Hyb_16/2A_R1P7	60.50^{q}	73.00^{q}	148.50^{o}	54.07^{v}	8.12^{nop}	9.43^{wxy}	1.46^{stuvw}	11.98^{stu}	12.29^{uvwx}
3	Hyb_16/2A_R1P9	63.50^{mn}	79.50^{fg}	150.50^{m}	153.23^{jklmn}	9.33^{m}	14.90^{klmn}	1.14^{vw}	11.15^{vwx}	11.27^{y}
4	Hyb_16/2A_R1P13	66.50^{i}	79.50^{fg}	149.50^{n}	125.15^{lmnopq}	11.25^{fg}	13.42^{opqrst}	1.16^{vw}	12.43^{qrs}	11.86^{xy}
5	Hyb_16/2A_R1P14	69.50^{cd}	83.50^{b}	151.50^{l}	135.88^{klmno}	9.63^{klm}	15.07^{klmn}	2.51^{jklm}	16.35^{bcd}	16.31^{ef}
6	Hyb_16/2A_R1P15	62.50^{o}	81.50^{de}	160.00^{f}	123.88^{lmnopq}	7.85^{nopqr}	14.62^{mno}	1.39^{tuvw}	13.86^{ghijklm}	13.10^{qrst}
7	Hyb_16/2A_R1P18	65.50^{j}	79.00^{gh}	162.00^{d}	120.72^{mnopq}	7.68^{opqr}	13.32^{pqrst}	0.72^{x}	10.59^{x}	10.56^{z}
8	Hyb_16/2A_R1P19	59.50^{r}	76.50^{klm}	161.00^{e}	101.00^{opqrstu}	10.20^{ijkl}	14.03^{nopq}	2.55^{jklm}	9.83^{y}	9.96^{z}
9	Hyb_16/2A_R1P20	62.50^{o}	80.50^{ef}	159.50^{f}	120.55^{mnopq}	7.15^{rs}	12.65st	2.40^{lmn}	13.64^{hijklm}	13.42^{pqrs}
10	Hyb_16/2A_R2P11	60.50^{q}	78.50^{ghi}	159.50^{f}	128.85^{klmnop}	7.30^{qrs}	12.81^{qrst}	2.68^{ijklm}	16.91^{b}	17.98^{bc}
11	Hyb_16/2A_R2P12	60.50^{q}	79.50^{fg}	154.00^{ij}	232.65^{ef}	12.32^{de}	15.97^{hijkl}	2.79^{ijk}	14.16^{fghi}	14.92^{hi}
12	Hyb_16/2A_R2P16	61.50^{p}	81.50^{de}	156.00^{h}	76.77^{stuv}	6.82^{s}	8.55^{yz}	1.68^{qrst}	13.47^{ijklmn}	14.32^{ijklmn}
13	Hyb_16/2A_R3P1	61.50^{p}	81.50^{de}	151.50^{l}	137.55^{klmno}	10.32^{ijkl}	16.60^{hij}	3.24^{h}	13.28^{klmnop}	13.82^{nop}
14	Hyb_16/2A_R3P2	60.50^{q}	78.50^{ghi}	152.50^{k}	114.83^{nopqrs}	7.88^{nopqr}	14.52^{mnop}	2.72^{ijkl}	13.21^{mnop}	13.02^{qrst}
15	Hyb_16/2A_R3P3	61.50^{p}	76.50^{klm}	158.00^{g}	74.42^{tuv}	9.95^{jklm}	8.07^{z}	4.24^{fg}	12.68^{pqr}	12.81^{rstuv}
16	Hyb_16/2A_R3P10	61.50^{p}	74.50^{op}	146.50^{q}	79.35^{rstuv}	11.27^{fg}	9.35^{wxy}	4.09^{g}	12.84^{nopq}	13.44^{pqr}
17	Hyb_16/2A_R3P18	59.50^{r}	81.00^{de}	145.50^{r}	94.45^{pqrstu}	8.15^{nop}	10.45^{vw}	4.85^{cd}	12.30^{qrst}	12.64^{tuvw}
18	Hyb_16/2A_R4P3	59.50^{r}	77.50^{ijk}	157.50^{g}	125.90^{lmnopq}	9.53^{lm}	12.92^{qrst}	2.80^{ijk}	11.55^{uvw}	12.17^{vwx}
19	Hyb_16/2A_R4P7	64.50^{kl}	82.00^{cd}	149.50^{n}	199.42^{fghi}	12.72^{cd}	9.97^{wx}	4.65^{de}	13.98^{fghij}	13.54^{opq}
20	Hyb_16/2A_R4P9	65.50^{j}	78.00^{hij}	150.50^{m}	68.72^{uv}	7.88^{nopqr}	8.85^{xyz}	4.47^{ef}	13.75^{hijklm}	14.05^{lmnop}
21	Hyb_16/2A_R4P10	70.50^{b}	81.50^{de}	153.50^{j}	106.82^{opqrstu}	8.12^{nop}	11.32^{uv}	5.12^{bc}	14.56^{ef}	14.70^{ijkl}
22	Hyb_16/2A_R4P13	68.50^{ef}	78.50^{ghi}	159.50^{f}	166.95^{hijk}	10.52^{ghij}	15.77^{ijklm}	5.60^{a}	14.59^{ef}	14.80^{hijk}
23	Hyb_16/2A_R5P8	63.50^{mn}	75.50^{mno}	164.50^{c}	121.85^{mnopq}	10.03^{ijklm}	14.72^{lmn}	2.51^{jklm}	14.87^{e}	15.89^{fg}
24	Hyb_16/2A_R5P9	67.00^{hi}	73.00^{q}	167.50^{b}	71.35^{tuv}	11.22^{fg}	12.28^{tu}	1.25^{uvw}	13.27^{klmnop}	13.99^{mnop}
25	Perlette	64.00^{lm}	75.50^{mno}	141.50^{v}	354.18^{c}	11.23^{fg}	20.22^{c}	1.80^{pqrs}	14.08^{fghij}	14.18^{klmno}
26	Hur	68.00^{fg}	79.50^{fg}	145.50^{r}	212.90^{efg}	11.15^{fgh}	17.11^{fgh}	2.71^{ijkl}	15.71^{d}	16.78^{de}
27	Bharat Early	65.00^{jk}	75.50^{mno}	139.50^{w}	108.85^{opqrst}	7.97^{nopq}	12.57^{t}	2.51^{jklm}	14.51^{efg}	14.53^{ijklm}
28	Anab-e-Shahi	69.00^{de}	80.50^{ef}	142.50^{u}	188.43^{ghij}	10.22^{ijkl}	18.81^{de}	4.89^{cd}	16.48^{bc}	17.38^{cd}
29	PusaUravashi	65.00^{jk}	77.00^{jkl}	148.50^{o}	361.38^{c}	13.28^{bc}	19.18^{cd}	2.68^{ijklm}	13.95^{fghijk}	14.87^{hij}
30	Black Prince	70.00^{bc}	81.50^{de}	150.50^{m}	95.47^{pqrstu}	7.40^{pqrs}	12.62^{t}	2.86^{ij}	13.92^{fghijk}	18.73^{a}
31	Julesky Muscat	60.00^{qr}	71.50^{r}	136.50^{x}	75.45^{tuv}	7.48^{pqrs}	13.90^{nopqrs}	1.85^{pqr}	13.77^{hijklm}	14.24^{jklmn}
32	Black Muscat	65.00^{jk}	74.50^{op}	155.50^{h}	133.42^{klmnop}	8.48^{no}	12.62^{t}	2.30^{mno}	13.74^{hijklm}	14.54^{ijklm}
33	Pusa Aditi	65.00^{jk}	77.00^{jkl}	143.50^{t}	336.38^{cd}	11.92^{def}	21.52^{b}	1.58^{rstu}	13.44^{jklmno}	14.59^{ijklm}
34	Pusa Seedless	70.00^{bc}	83.00^{bc}	142.50^{u}	201.32^{fgh}	10.15^{ijkl}	16.05^{hijk}	2.11^{nop}	12.81^{nopq}	15.87^{fg}
35	PusaTrishar	63.00^{no}	75.00^{no}	144.50^{s}	477.35^{a}	14.12^{a}	25.12^{a}	2.46^{klmn}	14.29^{efgh}	14.03^{lmnop}
36	Beauty Seedless	63.50^{mn}	76.00^{lmn}	151.50^{l}	303.38^{d}	12.38^{de}	22.22^{b}	1.52^{rstuv}	12.01^{rstu}	11.94^{xy}
37	Centennial seedless	68.50^{ef}	80.50^{ef}	142.50^{u}	157.15^{jklm}	10.12^{ijklm}	12.75^{rst}	1.87^{pqr}	13.24^{lmnop}	16.73^{de}
38	Cardinal	67.50^{gh}	79.50^{fg}	141.50^{v}	349.60^{c}	12.25^{de}	18.28^{def}	4.81^{cde}	11.25^{vwx}	12.08^{wx}
39	PusaNavrang	67.50^{gh}	77.50^{ijk}	142.50^{u}	115.25^{nopqrs}	11.72^{ef}	13.88^{nopqrs}	0.74^{x}	10.99^{wx}	10.25^{z}
40	Pearl of Casaba	61.50^{p}	72.50^{qr}	135.50^{y}	247.03^{e}	12.60^{cd}	17.90^{efg}	2.84^{ij}	16.30^{bcd}	15.95^{fg}
41	Banqui Abyad	63.50^{mn}	75.50^{mno}	153.50^{j}	189.78^{ghij}	8.45^{no}	12.72^{rst}	2.54^{jklm}	13.71^{hijklm}	17.38^{cd}
42	ER_R1P16	65.50^{j}	76.50^{klm}	150.50^{m}	116.90^{nopqr}	10.80^{ghi}	13.08^{qrst}	1.56^{rstu}	11.77^{stuv}	12.75^{stuv}
43	Flame seedless	65.50^{j}	77.50^{ijk}	159.50^{f}	338.48^{v}	10.32^{ijkl}	16.85^{ghi}	2.00^{opq}	13.68^{hijklm}	15.38^{gh}
44	Pusa Purple seedless	64.50^{kl}	76.50^{klm}	155.50^{h}	238.17^{ef}	9.67^{klm}	25.57^{a}	1.60^{rstu}	12.27^{qrst}	13.46^{pqr}
45	Punjab Purble	63.50^{mn}	73.50^{pq}	154.50^{i}	161.78^{ijkl}	10.35^{hijk}	13.92^{nopqr}	1.46^{stuvw}	12.77^{opq}	12.91^{qrstu}
46	Vitis parviflora	73.50^{a}	87.50^{a}	173.00^{a}	106.15^{opqrstu}	7.95^{nopqr}	13.27^{pqrst}	1.47^{stuv}	11.71^{tuv}	12.30^{uvwx}
47	PusaSwarnika	64.50^{kl}	75.50^{mno}	147.50^{p}	401.65^{b}	14.08^{ab}	22.22^{b}	5.42^{ab}	17.69^{a}	18.40^{ab}
48	Hyb_72-151	65.50^{j}	77.50^{ijk}	154.50^{i}	213.32^{efg}	10.25^{ijkl}	15.43^{jklm}	3.02^{hi}	15.87^{cd}	17.71^{c}
	Mean	64.46	78.50	151.43	148.31	9.96	14.86	2.62	13.48	14.16
	C.D.	0.655	6.51	0.165	0.013	0.180	0.014	0.071	0.097	0.063
	SE(m)	0.230	2.31	0.058	0.005	0.063	0.005	0.025	0.034	0.022
	SE(d)	0.325	3.27	0.082	0.007	0.089	0.007	0.035	0.048	0.031
	C.V.	0.458	10.19	0.646	0.082	0.988	0.095	1.378	0.727	0.64

Mean values followed by the same alphabetical letter(s) are not significant, whereas mean values with different alphabetical letter(s) differ significantly at $p \leq 0.05$. Hyb-Hybrid, ER-Embyo Rescue.

Bunch and berry parameters

Grape bunch and berry traits varied significantly across the 48 genotypes in both years as well as in the pooled analysis, indicating substantial genetic diversity for these characteristics (Tables 2–5; Fig. 1, 2). Bunch weight exhibited wide variation, with Pusa Trishar recording the highest value (477.35 g), followed by Pusa Swarnika (401.65 g), Pusa Urvashi (361.38 g), Perlette (354.18 g) and Cardinal (349.60 g). In contrast, Hyb_16_2A_R1P7 (54.07 g) and Hyb_16_2A_R3P3 (74.42 g) had the lowest bunch weights. The high standard deviation (SD = 86.27) and strong positive skewness (1.28) observed for bunch weight indicate considerable variability and a predominance of small- to medium-sized bunches.

Bunch width ranged from 6.82 cm (Hyb_16_2A_R2P16) to 14.12 cm (Pusa Trishar), while bunch length varied from 8.07 cm (Hyb_16_2A_R3P3) to 25.57 cm (Pusa Purple Seedless). Other genotypes exhibiting long bunches included Beauty Seedless (22.22 cm), Pusa Aditi (21.52 cm) and Pusa Trishar (25.12 cm). Both bunch width and length showed substantial variation (SD = 1.93 cm and 4.05 cm respectively) with slight positive skewness, suggesting that medium-sized bunch architecture was more prevalent among the evaluated germplasms.

Bunch density classes ranged from very loose (score 1) to highly dense (score 9). Several commercial varieties such as Perlette, Pusa Urvashi, Black Muscat, Pusa Seedless, Beauty Seedless, Banqui Abyad and Flame Seedless, along with hybrids including

Table 5. Qualitative pomological variability of the studied grape genotypes

Sl. No	Genotypes	Bunch density (Score values)		Bunch peduncle length (Score values)		Berry shape (Score values)		Berry size (Score values)		Berry Presence of seed (Score values)		Berry skin colour (Score values)	
1	Hyb_16/2A_R1P2	Medium	5	Very long	9	Round	4	6	1	Present	1	Blue black	6
2	Hyb_16/2A_R1P7	Medium	5	Short	3	Round	4	1	3	Present	1	Blue black	6
3	Hyb_16/2A_R1P9	Dense	7	Mediun	5	Round	4	1	1	Absent	0	Green yellow	1
4	Hyb_16/2A_R1P13	Dense	7	Short	3	Round	4	6	1	Absent	0	Green yellow	1
5	Hyb_16/2A_R1P14	Medium	5	Medium	5	Round	4	1	5	Present	1	Blue black	6
6	Hyb_16/2A_R1P15	Very dense	9	Very short	1	Round	4	6	3	Absent	0	Green yellow	1
7	Hyb_16/2A_R1P18	Dense	7	Very short	1	Round	4	6	1	Present	1	Blue black	6
8	Hyb_16/2A_R1P19	Very loose	1	Long	7	Round	4	6	5	Present	1	Blue black	6
9	Hyb_16/2A_R1P20	Very dense	9	Very short	9	Oblate	5	1	5	Present	1	Blue black	6
10	Hyb_16/2A_R2P11	Medium	5	Medium	5	Round	4	1	7	Present	1	Green yellow	1
11	Hyb_16/2A_R2P12	Dense	7	Medium	5	Round	4	6	5	Present	1	Green yellow	1
12	Hyb_16/2A_R2P16	Medium	5	Medium	5	Round	4	6	3	Present	1	Blue black	6
13	Hyb_16/2A_R3P1	Medium	5	Very short	1	Round	4	6	5	Present	1	Blue black	6
14	Hyb_16/2A_R3P2	Medium	5	Medium	5	Round	4	6	5	Present	1	Blue black	6
15	Hyb_16/2A_R3P3	Medium	5	Medium	5	Round	4	6	7	Present	1	Blue black	6
16	Hyb_16/2A_R3P10	Medium	5	Short	3	Oblate	5	6	7	Present	1	Blue black	6
17	Hyb_16/2A_R3P18	Dense	7	Very short	1	Oblate	5	6	7	Present	1	Blue black	6
18	Hyb_16/2A_R4P3	Medium	5	Very long	9	Round	4	6	5	Present	1	Blue black	6
19	Hyb_16/2A_R4P7	Very dense	9	Short	3	Oblate	5	6	7	Present	1	Blue black	6
20	Hyb_16/2A_R4P9	Medium	5	Medium	5	Round	4	6	7	Present	1	Blue black	6
21	Hyb_16/2A_R4P10	Dense	7	Very short	1	Round	4	6	7	Present	1	Blue black	6
22	Hyb_16/2A_R4P13	Medium	5	Short	3	Round	4	6	7	Present	1	Blue black	6
23	Hyb_16/2A_R5P8	Very loose	1	Long	7	obtuse ovate	7	6	5	Present	1	Blue black	6
24	Hyb_16/2A_R5P9	Loose	3	Medium	5	Oblate	5	1	3	Present	1	Blue black	6
25	Perlette	Very dense	9	Medium	5	Oblate	5	1	3	Absent	0	Green yellow	1
26	Hur	Medium	5	Short	3	Round	4	1	5	Present	1	Green yellow	1
27	Bharat Early	Medium	5	Medium	5	Oblate	5	1	5	Present	1	Green yellow	1
28	Anab-e-Shahi	Medium	5	Long	7	Round	4	1	7	Present	1	Green yellow	1
29	PusaUravashi	Very dense	9	Very short	1	Round	4	4	5	Absent	0	Green yellow	1
30	Black Prince	Dense	7	Medium	5	Oblong	1	1	5	Present	1	Red grey	4
31	Julesky Muscat	Medium	5	Short	3	Oblate	5	4	3	Present	1	Green yellow	1
32	Black Muscat	Very dense	9	Very short	1	obtuse ovate	7	1	3	Present	1	Red grey	4
33	Pusa Aditi	Dense	7	Medium	5	Round	4	1	3	Absent	0	Green yellow	1
34	Pusa Seedless	Very dense	9	Short	3	Oblong	1	1	3	Absent	0	Green yellow	1
35	PusaTrishar	Dense	7	Long	7	Round	4	6	5	Absent	0	Green yellow	1
36	Beauty Seedless	Very dense	9	Medium	5	Round	4	1	3	Absent	0	Blue black	6
37	Centennial seedless	Medium	5	Very short	1	Round	4	5	3	Absent	0	Green yellow	1
38	Cardinal	Loose	3	Long	7	Round	4	6	7	Present	1	dark red violet	5
39	PusaNavrang	Loose	3	Very long	9	Round	4	1	1	Present	1	Blue black	6
40	Pearl of Csaba	Medium	5	Medium	5	Round	4	4	5	Present	1	Green yellow	1
41	Banqui Abyad	Very dense	9	Very short	1	Oblong	1	6	5	Present	1	rose grey	4
42	ER_R1P16	Medium	5	Short	3	Round	4	4	3	Absent	0	Blue black	6
43	Flame seedless	Very dense	9	Very short	1	Elliptic	3	6	5	Absent	0	Red grey	4
44	Pusa Purple seedless	Loose	3	Very long	9	Round	4	6	3	Absent	0	Blue black	6
45	Punjab Purble	Dense	7	Short	3	Round	4	6	3	Present	1	Blue black	6
46	Vitis parviflora	Medium	5	Medium	5	Round	4	1	3	Present	1	Blue black	6
47	PusaSwarnika	Loose	3	Short	3	Round	4	1	7	Present	1	Green yellow	1
48	Hyb_72-151	Medium	5	Medium	5	Round	4	Medium	5	Absent	0	Green yellow	1

Hyb_16_2A_R1P15, Hyb_16_2A_R1P18, Hyb_16_2A_R4P7 and Hyb_16_2A_R5P20, displayed extremely dense bunches (score 9). Conversely, loose to very loose bunch density (score 1–3) was observed in Hyb_16_2A_R1P19, Hyb_16_2A_R5P8, Cardinal, Pusa Navrang, Pusa Purple Seedless and Pusa Swarnika.

Bunch peduncle length also exhibited wide variation, ranging from very short (score 1) to very long (score 9). Genotypes such as Hyb_16_2A_R1P2, Hyb_16_2A_R4P3, Pusa Navrang and Pusa Purple Seedless had extremely long peduncles, facilitating easier handling and reducing compression damage during harvest and postharvest operations. Conversely, very short peduncles (score 1) in Hyb_16_2A_R1P15, Hyb_16_2A_R1P18, Hyb_16_2A_R3P1, Hyb_16_2A_R3P18, Black Muscat, Flame Seedless, Banqui Abyad and Pusa Urvashi indicate compact clusters with tightly attached berries. Berry traits exhibited wide and significant variation among the 48 grape genotypes. Berry weight ranged from 0.72 g in Hyb_16_2A_R1P18 and 0.74 g in Pusa Navrang to 5.60 g in Hyb_16_2A_R4P13, followed by Pusa Swarnika (5.42 g), Hyb_16_2A_R4P10 (5.12 g) and Hyb_16_2A_R3P18 (4.85 g), demonstrating strong genotypic effects on berry size.

Berry width ranged from 9.83 mm (Hyb_16_2A_R1P19) to 17.69 mm (Pusa Swarnika), with several other large-berried genotypes, including Hyb_16_2A_R2P11 (16.91 mm), Anab-e-Shahi (16.48 mm) and Pearl of Csaba (16.30 mm). The smallest berry widths were recorded in Hyb_16_2A_R1P18 (10.59 mm) and Pusa Navrang (10.99 mm). Many genotypes including Black Prince, Black Muscat, Julesky Muscat, Pusa Aditi, Beauty Seedless and several hybrids fell within the medium width class (12–14.5 mm), reflecting the general preference for moderate berry diameter in both table and processing grapes. Berry length also showed significant variability, ranging from 9.96 mm in Hyb_16_2A_R1P19 to 18.73 mm in Black Prince. Most genotypes, including Perlette, Pusa Aditi, Pusa Seedless, Bharat Early, Julesky Muscat and several hybrids, exhibited intermediate berry length (12–15 mm), consistent with the commercial selection trends for medium-sized berries in seedless table grape markets.

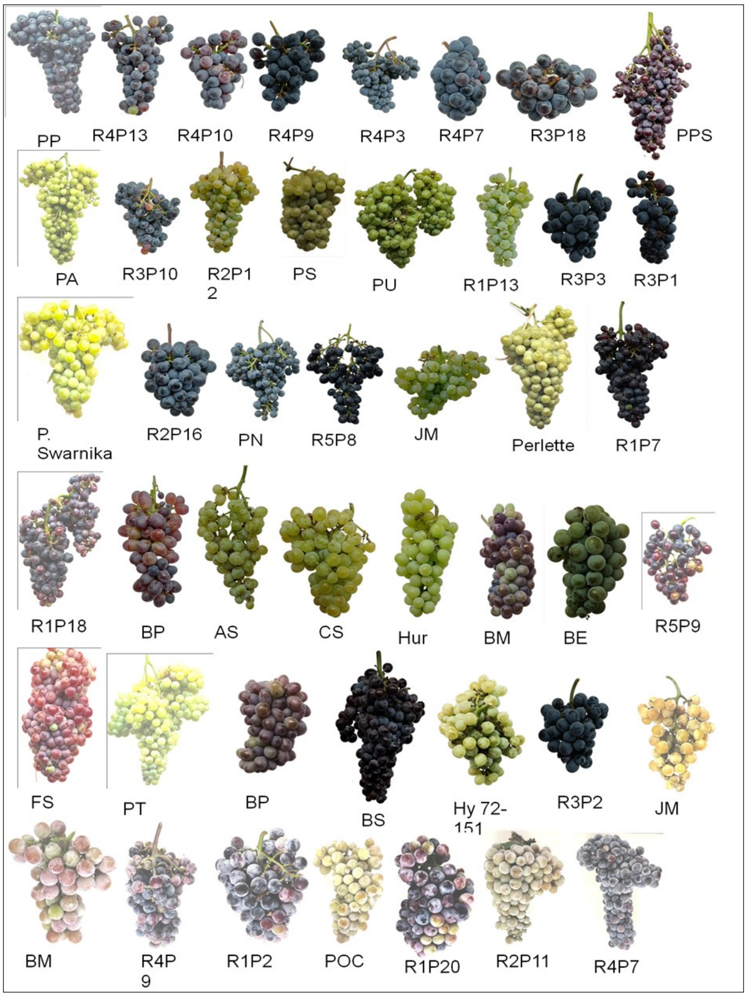

Fig. 1. Variations in the bunch attributes of the studied grape cultivars at the maturity stage.

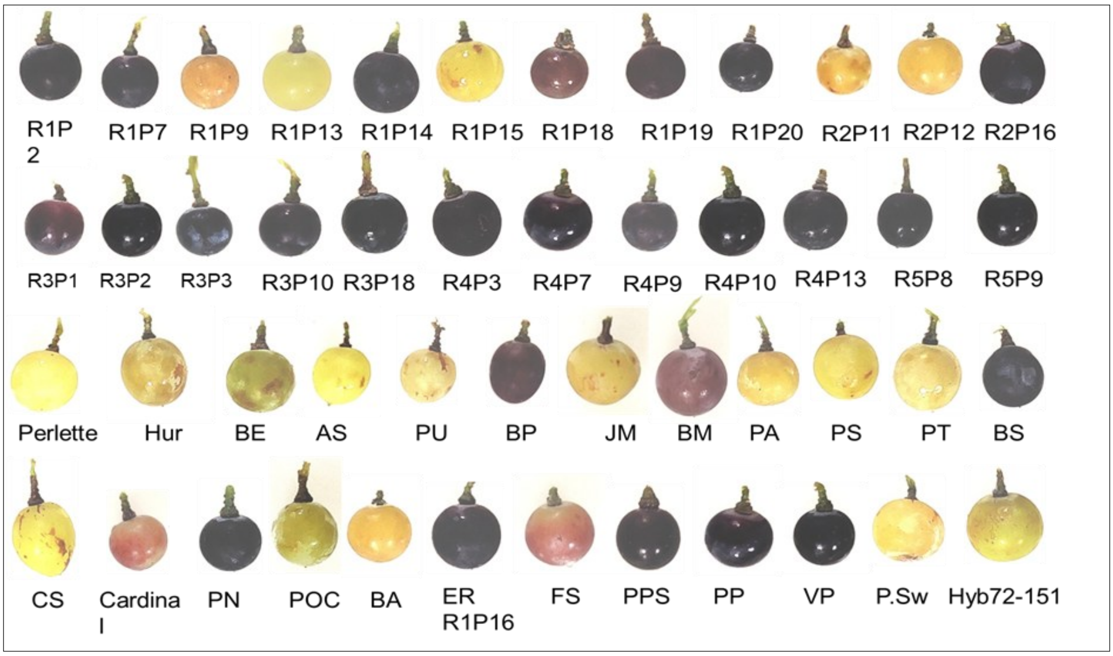

Fig. 2. The mature berries of the studied grape cultivars, showing variations for berry colour and berry morphological attributes.

Berry shape was predominantly round (IPGRI score 4), accounting for more than 70 % of the genotypes, which aligns with the preferred morphological type for table grapes. The oblate shape (score 5) was also well represented, occurring in genotypes such as Hyb_16_2A_R1P20, Hyb_16_2A_R3P10, Hyb_16_2A_R3P18, Hyb_16_2A_R4P7, Hyb_16_2A_R5P9, Perlette, Bharat Early, Julesky Muscat and Pusa Purple Seedless. A few genotypes displayed oblong or elliptic forms, including Black Prince, Pusa Seedless, Banqui Abyad (oblong, score 1) and Flame Seedless (elliptic, score 3), indicating broader morphological diversity within the germplasm. Berry size categories (IPGRI scores 1–7) further revealed considerable differentiation. Genotypes such as Hyb_16_2A_R1P2, Hyb_16_2A_R1P9, Hyb_16_2A_R1P13, Hyb_16_2A_R1P18 and Pusa Navrang fell into the very small berry class, making them unsuitable for table purposes but potentially valuable as breeding parents or for processing applications. In contrast, several genotypes, including

Hyb_16_2A_R2P11, Hyb_16_2A_R3P3, Hyb_16_2A_R3P10, Hyb_16_2A_R3P18, Hyb_16_2A_R4P7, Hyb_16_2A_R4P9, Hyb_16_2A_R4P10, Hyb_16_2A_R4P13, Anab-e-Shahi, Cardinal, Pusa Swarnika and Hyb_16_2A_R4P20, belonged to the large berry class (score 7), making them promising for table grape improvement programmes.

Berry skin colour also varied markedly among the genotypes, falling into four IPGRI colour categories: green-yellow (score 1), red-grey (score 4), dark red violet (score 5) and blue-black (score 6). The blue-black group was the most predominant, represented by 24 genotypes, including numerous hybrids (Hyb_16_2A series), Pusa Navrang, Punjab Purple, Black Prince and Beauty Seedless. The green-yellow class included 18 genotypes. Five genotypes belonged to the red-grey category, while only one genotype, Cardinal, exhibited the dark red violet colouration. Seedlessness was observed in 19 genotypes (39.58 %), while 29 genotypes (60.42 %) were seeded. The substantial proportion of seedless types highlights their potential suitability for table grape breeding under subtropical conditions, where consumer preference strongly favours seedlessness.

Pearson's correlations among the traits

Pearson correlation coefficient among the examined traits revealed that the contributing features, bunch weight, was shown to be strongly and positively correlated with bunch length (r = 0.82), bunch width (r = 0.73) and berry weight (r = 0.42) (Fig. 3). Individual berry weight and bunch size features are crucial selection variables for increasing production since they are likely to produce heavier bunches. Likewise, there was a high positive connection between berry weight and both berry width (r = 0.86) and berry length (r = 0.85), indicating that both dimensional parameters have a significant role in total berry mass. Together, these 3 traits make up the fundamental element of fruit size, which is a significant factor in determining yield and market choice. However, traits like bunch weight (r = -0.26 and -0.28 respectively) and berry size parameters were negatively correlated with berry colour (Ber.Co) and bunch density (Bun.den), suggesting that tighter bunches typically had smaller berries and lower total bunch weight. Intriguingly, phenological traits like DH, days to panicle emergence (DPE) and days to first bloom (DFB) exhibited weak correlations with traits related to yield, indicating that in the current genetic material, berry size or bunch yield is not significantly impacted by early or late flowering or harvest. DFB and DPE showed a somewhat positive connection (r = 0.50).

Principal component analysis (PCA)

In PCA, the first 5 principal components (PCs) explained 74 % of the variance, with PC1 accounting for 24 %, PC2 (19 %), PC3 (14 %), PC4 (9 %) and PC5 (8 %) respectively. This suggests that the first few components are crucial for trait selection and genotype discrimination, as they capture most of the phenotypic variability. PC1 was significantly influenced by berry width (0.32), berry length (0.32), bunch weight (0.44), bunch length (0.36) and bunch width (0.33), indicating that PC1 primarily reflects morphological features that contribute to yield. These characteristics are essential for market value and productivity, suggesting that genotypes with high PC1 scores may have higher yield potential. Berry weight (0.48), berry size (0.50), berry width (0.35) and berry length (0.32) were the main factors influencing PC2, which accounted for 19 % of the variance. When evaluating table grape fruit quality, this component records variations in berry size and shape. Phenological and structural trait variation was captured by PC3 (14 %) and included a positive contribution from bunch peduncle length (0.37) and a high negative loading from DFB (-0.47), DPE (-0.34) and bunch density (-0.38). Both cluster compactness and flowering behaviour depend on these characteristics. While PC5 was impacted by berry weight (0.37),

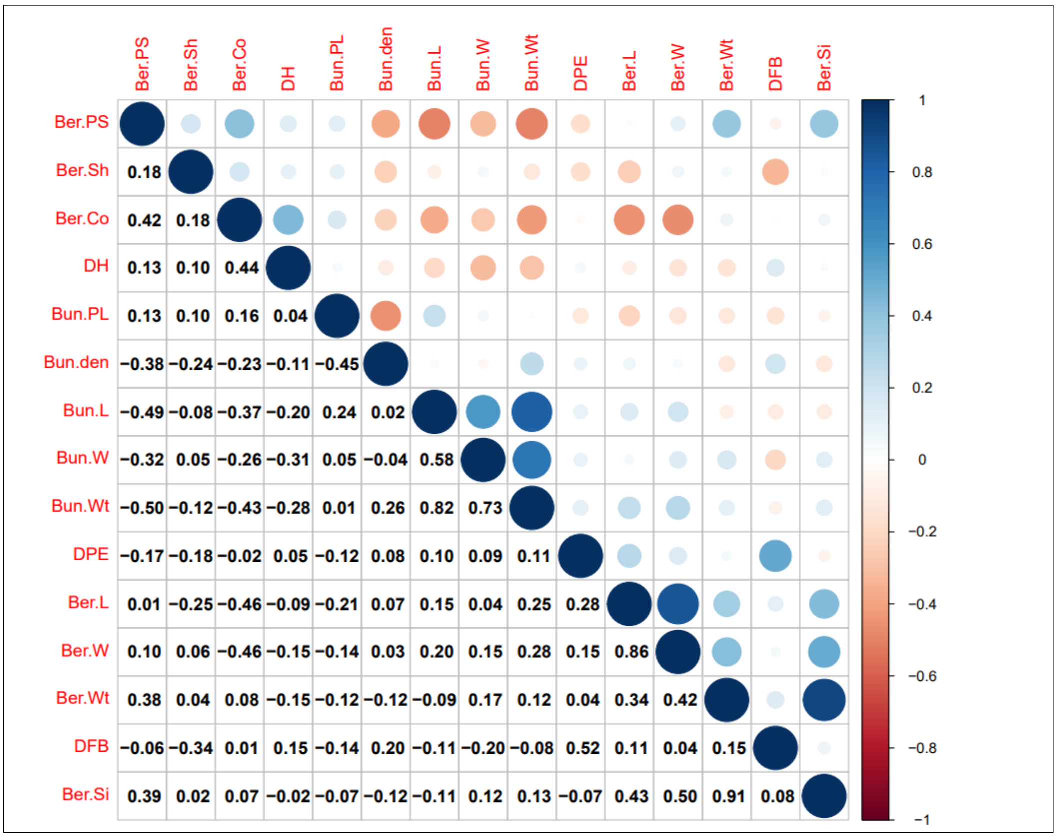

Fig. 3. Pearson's correlation matrix showing the strength and direction of linear relationships among the morphological-pomological traits assessed across 48 grape genotypes. Positive and negative correlations are indicated by colour intensity.

bunch density (0.35) and berry colour (0.31), PC4 displayed notable loadings from DPE (-0.49), DFB (-0.41) and bunch peduncle length (-0.38), once more highlighting flowering and maturity features. Subsequent components (PC6 to PC15) represented finer variations and accounted for a little less than 6 % of the total variance each. Some distinct trait-specific impacts were still noted, though, including significant contributions from berry length (PC14, -0.62) and shape (PC6, -0.64) (Table 6 and Fig. 4).

The PCA biplot based on the first 2 principal components (PC1 and PC2) together accounts for 43 % of the total phenotypic variation and shows key traits underlying the variation along the dimensions. Pusa Swarnika, Pusa Trishar, Perlette and Pusa Urvashi are genotypes that are far from the origin. These genotypes exhibited substantial divergence and represented extreme manifestations of traits such as enormous berry size, heavy bunch weight and extended bunch length. In contrast, many Hyb_16_2A selections were located near the origin on the left side of the biplot, indicating more moderate phenotypic expression and smaller bunches and berries. Cardinal, Black Muscat, Flame Seedless and Julesky Muscat were among the genotypes that grouped close to the centre, displayed intermediate trait values and made very little contribution to overall variation. Large-berried and long-cluster genotypes like Anab-e-Shahi and Hur emerged in the upper-right quadrant, while early-flowering and early-harvesting genotypes like Hyb_16_2A_R1P19 and Hyb_16_2A_R5P9 gathered in the upper-left region. Overall, it is evident from the biplot that there are 2 main clusters of traits: one linked to size and yield (Bun.Wt, Ber.Wt, Ber.L, Ber.W, Bun.L, Bun.W) and the other to compactness and phenology (DPE, DFB, DH, Bun.den, Ber.Co). The results from the correlation and PCA loading tables are corroborated by this graphic representation, which offers a tactical framework for locating genotypes with desired combinations of high yield and fruit quality attributes for breeding initiatives (Fig. 5).

Table 6. Principal component analysis of studied parameters for grape genotypes under subtropical conditions

		PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
SD		1.91	1.69	1.47	1.18	1.07	0.99	0.9	0.75	0.68	0.58	0.54	0.44	0.31	0.25	0.2
Var		0.24	0.19	0.14	0.09	0.08	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0	0
Cum. Var.		0.24	0.43	0.58	0.67	0.74	0.81	0.86	0.9	0.93	0.95	0.97	0.99	0.99	1	1
Trait contribution	Bun.Wt	0.44	-0.15	0.16	-0.14	0.2	-0.1	0.18	-0.04	0.12	-0.15	0.1	-0.12	0.66	0.12	0.37
	Bun.L	0.36	-0.24	0.22	-0.26	-0.07	-0.06	0.19	-0.09	0.07	-0.19	0.57	-0.12	-0.41	-0.09	-0.31
	Bun.W	0.33	-0.11	0.31	-0.17	0.29	-0.07	-0.17	0.32	-0.09	-0.23	-0.55	0.31	-0.19	-0.13	-0.13
	Ber.Wt	0.13	0.48	0.11	-0.09	0.37	0.1	-0.04	-0.09	-0.11	0.18	0.1	-0.24	-0.34	-0.31	0.5
	Ber.W	0.32	0.35	0	0.12	-0.36	-0.21	0	-0.12	0.11	-0.1	-0.03	0.35	-0.27	0.54	0.27
	Ber.L	0.32	0.32	-0.16	0.07	-0.4	-0.07	0.13	0.19	0.15	0.16	0.02	0.21	0.24	-0.62	-0.14
	DPE	0.13	0.03	-0.34	-0.49	-0.09	-0.15	-0.5	0.2	0.32	0.19	-0.07	-0.36	-0.02	0.15	-0.05
	DFB	0.03	0.1	-0.47	-0.41	0.08	0.13	-0.11	-0.44	-0.36	-0.34	0.05	0.32	0.11	-0.1	-0.05
	DH	-0.23	0.05	-0.12	-0.31	-0.11	-0.57	0.55	0.12	-0.22	-0.1	-0.24	-0.22	-0.1	-0.03	0.09
	Bun.den	0.15	-0.14	-0.38	0.29	0.35	-0.15	0.2	-0.39	0.51	-0.03	-0.26	-0.06	-0.18	-0.11	-0.1
	Bun.PL	-0.09	-0.09	0.37	-0.38	-0.34	0.31	0.14	-0.46	0.24	0.22	-0.37	-0.01	-0.01	-0.07	0.06
	Ber.Sh	-0.13	0.05	0.35	0.12	-0.01	-0.64	-0.44	-0.42	-0.05	0.01	0.06	0	0.14	-0.19	-0.1
	Ber.Si	0.13	0.5	0.13	-0.05	0.27	0.04	0.2	-0.09	-0.11	0.24	-0.06	-0.12	0.19	0.32	-0.6
	Ber.PS	-0.25	0.39	0.15	0.02	-0.06	0.15	-0.05	0.08	0.36	-0.73	-0.02	-0.23	0.06	-0.07	-0.07
	Ber.Co	-0.37	0.08	0.08	-0.32	0.31	-0.13	0.11	0.15	0.43	0.17	0.28	0.55	0.03	0.02	0.05

Ber Si-Berry size; Ber.wt-Berry weight; Ber.W-Berry width; Ber.L-Berry length; DPE- Days to panicle emergence; Bun. W- Bunch width; Bun den-Bunch density; Bun.L- Bunch length; DPE- Days to panicle emergence; Bun W- Bunch width; Bun Wt- Bunch weight; Bun den- Bunch density; Bun L- Bunch length; Bun PL-Bunch peduncle length; DH- Days to harvest; Ber Co-Berry colour; Ber. Sh- Berry shape; Ber.PS- Berry presence of seed.

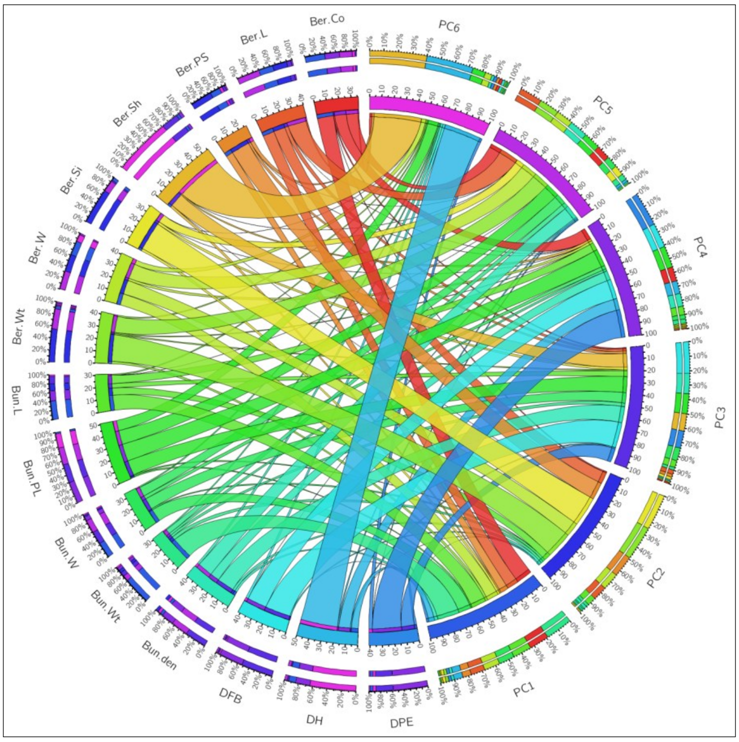

Fig. 4. The contribution of different traits of grape genotypes to the major principal component is graphically represented in circos diagram.

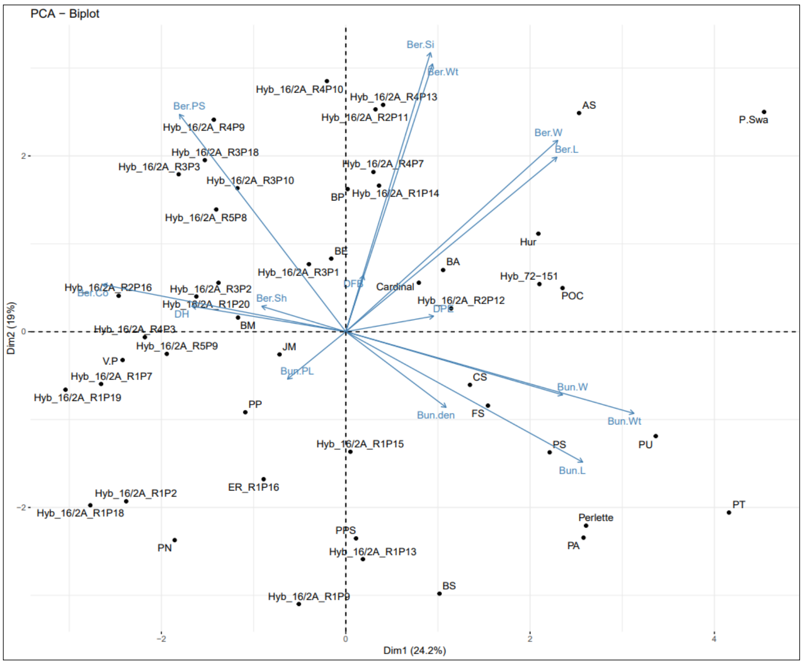

Fig. 5. PCA biplot depicting the distribution of the 48 grape genotypes and the contribution of morphological traits to the first two principal components. Ber Si-Berry size; Ber.wt-Berry weight; Ber.W-Berry width; Ber.L-Berry length; DPE- Days to panicle emergence; Bun. W- Bunch width, Bun. Wt- Bunch weight; Bun den- Bunch density; Bun.L- Bunch length; DPE- Days to panicle emergence; Bun W- Bunch width; Bun Wt-Bunch weight; Bun den- Bunch density; Bun L- Bunch length; Bun PL-Bunch peduncle length; DH- Days to harvest; Ber Co-Berry colour; Ber. Sh-Berry shape; Ber.PS- Berry presence of seed.

Hierarchical cluster analysis

Significant genetic heterogeneity within the germplasm is indicated by the grouping of 48 grape genotypes based on morphological and pomological variables, which reflects the combined impact of shared parentage, trait heritability and recombination. The development of 3 main clusters indicates that important quantitative characteristics that are known to have moderate to high heritability in grapevine, such as berry size, bunch architecture and phenology, have a significant impact on the genetic linkages between accessions. The Hyb 16/2A series hybrids' close grouping can be explained by their shared parental background and directional selection, which led to minimal allelic divergence and comparable phenotypic expression, a pattern frequently observed for grape hybrids with common parents. Commercial cultivars like Cardinal, Perlette, Pusa Seedless and Pusa Urvashi, on the other hand, are distributed because of their different genetic origins and separate breeding history; Cardinal, on the other hand, forms a distinct branch because of its distinctive phenotypic profile. The usefulness of morphological and pomological descriptors for grape germplasm characterisation and breeding is highlighted by the intermediate positioning of some hybrids, which shows mixed trait expression resulting from segregation and recombination of parental alleles (Fig. 6).

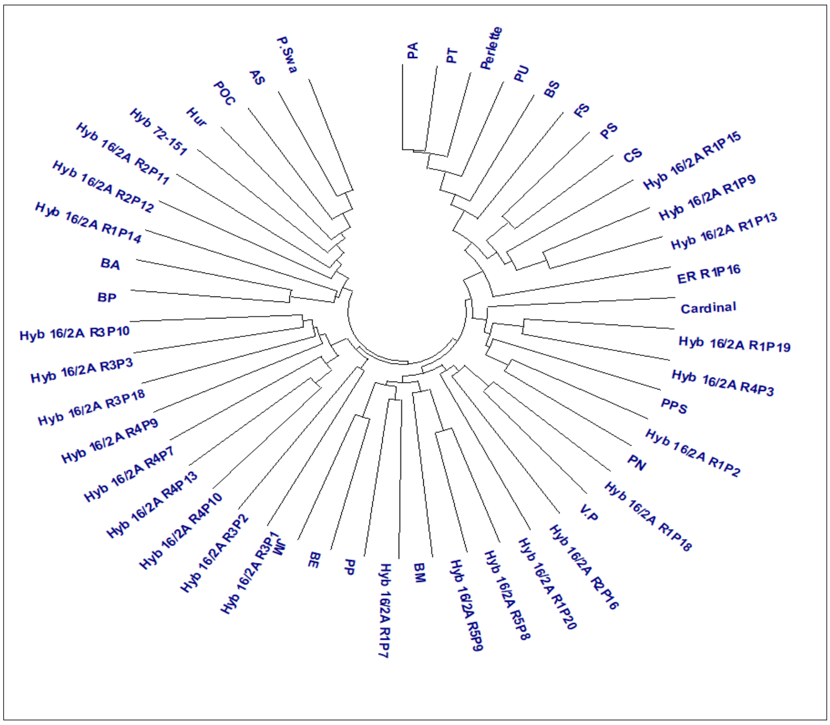

Fig. 6. Hierarchical cluster analysis of the 48 grape genotypes based on morphological traits using the unweighted pair group method with arithmetic mean (UPGMA) method and Euclidean distance matrix

Discussion

Under subtropical conditions, the pooled ANOVA showed significant genetic diversity across grape genotypes for the majority of phenotypic, bunch and berry traits. Bunch and berry attributes stayed mostly constant over years and genotype × year effects. Flowering parameters showed environmental sensitivity. Significant genetic variations in blooming time, maturity, bunch weight and berry size indicate a broad range of options for early and high-yielding varieties. Bunch and berry features are dependable selection criteria due to their great genetic control and stability. Days to panicle emergence was one of the morphological parameters with a restricted range and minimal dispersion, indicating stable genetic regulation. While late panicle emergence in *V. parviflora* indicates its greater thermal need, early panicle emergence in hybrids like Hyb_16/2A_R1P2, Hyb_16/2A_R1P19 and Julesky Muscat is beneficial for making effective use of the growing season and for developing early maturing varieties in grape breeding. Wider variation in days to full bloom and days to harvest allowed for the identification of early-maturing genotypes like Pearl of Csaba, Julesky Muscat and Bharat Early, which are useful for avoiding pre-monsoon showers during harvest, which also causes berry cracking and poor market value. Similar studies were made earlier in grapes (9, 19, 20).

There was noticeable genotypic heterogeneity in the grape varieties bunch and berry characteristics. It was found that Pusa Trishar, Pusa Swarnika, Pusa Urvashi and Perlette had higher bunch weights, which indicates improved production potential. Because it provides greater aeration, a loose to medium bunch density like that of Pusa Swarnika and Pusa Purple Seedless is favoured in subtropical climates. Larger berries were found in Hyb_16/2A_R4P13, Pusa Swarnika, Anab-e-Shahi and Black Prince, among other varieties. The market value of seedless cultivars like Perlette, Pusa Seedless, Flame Seedless and Beauty Seedless is higher. Overall, the large variability indicates a fair chance of choosing parents and cultivars with acceptable bunch and berry features to increase grape yield in subtropical climates. Similar results were observed for bunch and berry traits in grapes and for seedlessness and colour in grape berries (9, 19–21).

According to multivariate analysis, the main factors influencing genetic divergence among grape varieties in subtropical environments are bunch and fruit characteristics. With PC1 (24 %) mostly linked to bunch weight, bunch dimensions and berry size, PCA revealed that the first 5 components accounted for 74 % of the overall variation, emphasising yield-related variables as the main drivers of diversity. Berry weight and size metrics topped PC2 (19 %), highlighting their significance for table grape quality and consumer choice. Flowering and maturity-related phenological traits were most prevalent in PC3 and PC4, indicating that while phenology plays a role in subtropical adaptation, it is not as important as fruit attributes. The current results were consistent with earlier findings in grape (9, 19, 20, 22–24).

Larger bunch architecture directly increases yield, as demonstrated by the strong positive correlations found between bunch weight and bunch length ($r = 0.82$) and breadth ($r = 0.73$). Similarly, proportionate berry development is indicated by the strong correlations between berry size and weight ($r = 0.91$) and between berry length and breadth ($r = 0.86$). This suggests that size features might effectively select for fruit weight indirectly. Compact bunches are typically smaller, according to negative correlations found between bunch density and bunch size or weight. This could have an impact on yield and disease susceptibility in humid subtropical environments. It is beneficial for breeding programs since yield and berry quality can be improved substantially independently of crop duration, as seen by the modest relationships found between phenological variables and fruit features. The results are in line with the previous studies (9, 22, 23).

Clear genetic structuring among the 48 cultivars was also shown by cluster analysis; numerous hybrids clustered near released varieties including Cardinal, Pusa Seedless and Perlette, indicating common fruit trait profiles. On the other hand, because of their unique fruit and phenological traits, genotypes like *V. parviflora* and several hybrids created far-off clusters. Significant genetic variation is highlighted by the wide inter-cluster distances, providing ample opportunity to choose divergent parents to enhance fruit quality, production and subtropical adaptability. Overall, the findings reinforce previous research by demonstrating that selection focusing on bunch and berry size traits is essential to genetic improvement in subtropical table grapes, while phenological variables offer beneficial adaptation advantages for quality attributes (9, 19, 20, 22, 24, 25).

Conclusion

Wide genetic diversity in phenological, morphological and pomological variables with substantial genotype × year interactions was found when 48 grape genotypes were evaluated under subtropical conditions. Early flowering and early maturing genotypes, such as Pearl of Csaba and Julesky Muscat offer an adaptive advantage by avoiding heat and early monsoon showers. Exceptionally high bunch weight in Pusa Trishar, Pusa Swarnika, Pusa Urvashi and Perlette, indicating wide genetic diversity and strong scope for selection of high-yielding types. A wide variation in berry skin colour was observed, including blue-black, green-yellow, red-grey and dark red-violet, indicating significant phenotypic diversity and potential for selection based on consumer or processing requirements. Pusa Trishar, Pusa Swarnika and Pusa Urvashi are genotypes that have shown promising for increasing fruit quality and productivity. Breeding seedless, pigment-rich and climate-resilient cultivars is made possible by the variety in berry size, shape, colour and seed content. Hence, the identified genotypes are useful donors for tailoring high-yielding grape cultivars appropriate for subtropical viticulture.

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Authors' contributions

NMA, MKV, SKS, VBP, CK designed and planned and executed the experiment, NS, GPM and SN analysed the data using statistical softwares and gave discussion part, NMA, KV, KG, RS were involved in writing the manuscript, JP and MT were involved in correcting the manuscript.All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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