



RESEARCH ARTICLE

Genetic variability and multivariate analysis of fruit yield and quality traits in tomato (*Solanum lycopersicum* L.) genotypes

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Abstract

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop esteemed for its nutritional and antioxidant attributes, playing a crucial role in human health and food security. The current study was undertaken to assess the extent of genetic variability among three-jointed and seven-jointless pedicel tomato genotypes for fruit and quality traits and to identify superior genotypes for crop improvement programmes. The experiment was conducted using a completely randomised design (CRD) with 3 replications and significant differences were observed among genotypes for most traits, indicating ample scope for selection. The jointless pedicel genotype EC605094 exhibited superior performance for fruit size, fruit weight, firmness and juice yield, whereas New Jointless recorded higher antioxidant traits, including lycopene, β -carotene and ascorbic acid contents. Among the jointed pedicel varieties, Kashi Chayan showed desirable fruit quality traits, particularly for juice yield and carotenoid content. The analysis of genetic variability revealed substantial genotypic and phenotypic coefficients of variation for fruit weight. Fruit weight exhibited high heritability and significant genetic advance as a percent of the mean, indicating the prevalence of additive gene action and the efficacy of direct selection. Correlation analysis demonstrated a strong interrelationship among fruit size, weight and quality traits. Principal component analysis (PCA) identified four components responsible for 86.39 % of the total variation, with PC1 contributing 34.77 %. The identified superior jointed and jointless pedicel genotypes may serve as valuable parental lines for future tomato hybridisation programmes targeting higher yield and nutritional quality.

Keywords: genetic variability analysis; principal component analysis; quality character; tomato

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely grown crops worldwide due to its high economic and nutritional demand. In 2024, global tomato production reached approximately 188.50 Mt, cultivated over 5.12 Mha (1). China was the leading tomato producer with an annual production of 61.70 Mt, followed by India with 21.32 Mt (1). Tomatoes and tomato-based products offer various health benefits and play an important role in human nutrition (2). The tomato contains many vitamins, minerals, ascorbic acid and antioxidants, primarily beta-carotene and lycopene, as well as flavonoids and derivatives of hydroxycinnamic acid (3). The tomatoes' antioxidants, including lycopene, beta-carotene and phenolic compounds, have been linked to several health benefits, including anti-inflammatory, anti-cancer and antioxidant effects (4). These substances are also essential for controlling enzyme activity, preventing cellular damage and proliferation and neutralising dangerous reactive oxygen species (5). Due to their fundamental nutritional and health benefits, tomatoes are regarded as functional foods (6).

Lycopene constitutes 80–90 % of the carotenoid content in tomato fruit, whereas β -carotene accounts for approximately 7–10 % (7). Lycopene exhibits a high rate of singlet oxygen quenching and powerful antioxidant capabilities, while β -carotene is linked to provitamin A activity, skeletal muscle metabolism, prevention of spleen damage, neuroprotection and hypocholesterolemic effects (8–11). Such compounds may significantly reduce the risk of certain lethal diseases, especially cancer and coronary artery disease. Increased blood lycopene levels are associated with a reduced risk of prostate and other cancers (12, 13). The consumption of tomatoes correlates with elevated levels of lycopene in plasma and serum (14). Tomatoes are rich in phenolic compounds and possess desirable total soluble solids and pH characteristics (15). Titratable acidity, or total acidity level, quantifies the overall acid content in food and serves as a more reliable measure of the acids' effect on flavour. The phenolic compounds, vitamins, minerals and organic acids present in tomatoes facilitate various physiological activities, including the preservation of lipid metabolism, stimulation of blood circulation

and maintenance of bone structure (16).

Increasing consumer awareness regarding nutrition and crop quality has made the development of crop varieties with enhanced nutritional and antioxidant properties a major objective of agricultural improvement. In this context, identifying varieties with enhanced nutritional value is an effective strategy for selecting tomato genotypes that have improved nutritional advantages and health-promoting attributes. This study analysed 10 tomato genotypes to evaluate their fruit and quality traits and to identify superior varieties. Genetic variability and multivariate analysis pave the way for selecting better genotypes with good fruit and nutritional characteristics in a breeding programme.

Materials and Methods

Experimental design

This study included 10 tomato genotypes comprising three jointed pedicel varieties (Punjab Varkha Bahar-1, Kashi Aman and Kashi Chayan) and 7 jointless pedicel genotypes (New Jointless, VRT 69, EC695037, EC605094, EC62032, EC538441-3 and EC538439). The experiment was conducted using a completely randomised design (CRD) with 3 replications at ICAR-Indian Institute of Vegetable Research (IIVR), Varanasi, during March 2025. Ten tomato genotypes served as treatments and three fruits from each genotype were collected to document the fruit quality attributes.

Fruit characters

The fruit characters such as fruit length (cm), width (cm) and pericarp thickness (mm) were measured using a vernier calliper (VC-30, Baker Gauges India Pvt. Ltd, Pune, India). The weight of the fruits (g) was measured using a weighing balance (PGB 200, Helix Bioscience, New Delhi, India). The fruit texture (N) was measured using a texture analyser (TA XT2i M/s Stable Micro Systems, UK). A 9 point hedonic scale was used to assess the visual quality, where: 1 = very poor (significant pitting, overall degradation (> 50 %) and complete firmness loss); 3 = poor (moderate level of visual defects, ranging from 6 % to 50 %); 5 = good, marketability limit (defects range from 1–5 %, with modest shrivelling and a slight loss of firmness); 7 = very good (there is very little firmness loss and no pitting or decomposition on the fruits' surface); 9 = excellent (fruit is quite firm and there is no damage) (17). In order to match and characterise the colour of the tomato fruits, the panellists employed colour charts. According to a rating scale, the colour of the tomato fruit was evaluated as follows: 1 for "Green mature," 2 for "Breaker," 3 for "Turning," 4 for "Pink," 5 for "Light red," and 6 for "Red" (18). The number of seeds and locules per fruit was determined through visual observation.

Quality characters

The quality characters include pH measured using a pH meter (HBPH-11, Helix Bioscience, New Delhi, India) and total soluble solids (TSS) (°B) was estimated with a digital refractometer (Cat no. 3810, ATAGO CO., LTD). Lycopene (mg/100 g) and b-carotene (mg/100 g) were estimated using (19). Total sugars (%) were estimated using the anthrone method (20). The optical density values for Lycopene, b-carotene and total sugars were recorded by a UV-VIS spectrophotometer (Orion Aquamate 8000, Thermo Fisher Scientific Inc., Waltham, MA, USA). Ascorbic acid (mg/100 g) was estimated according to a previous study (21). Titratable acidity (%) was determined using (22). The sugar-acid ratio was computed by dividing the specified samples' total sugar content by its titratable

acidity (23). Fruit juice was extracted using a food processor (BXFP8001IN, Black & Decker, Towson, MD21286, USA) and fruit juice yield (%) was calculated (24).

Statistical analysis

Analysis of variance (ANOVA), Duncans' multiple range test (DMRT), genetic variability analysis and multivariate analysis such as Pearsons' correlation and principal component analysis were done using GRAPES software, Version 1.1.0. (25).

Results and Discussion

Analysis of variance

The significant mean sum of squares for each characteristic identified in the ANOVA study is presented in Table 1. Highly significant variation at 5 % level of significance was observed for fruit length, fruit width, fruit weight, number of seeds per fruit, number of locules per fruit, pericarp thickness, fruit texture, fruit juice yield, visual quality, fruit colour, total soluble solids, titratable acidity, ascorbic acid, lycopene, β -carotene and sugar-acid ratio. High *F*-values were observed for the traits viz., fruit weight (562.53), number of seeds per fruit (615.38) and ascorbic acid (180.60), indicating a higher degree of variability among genotypes and a lower degree of environmental influence on these traits. However, pH and total sugars were found to be non-significant, suggesting comparatively lower genetic variability and a greater influence of environmental factors on their expression. These results show a large scope for improvement of important traits of fruit yield and nutritional quality through selection and hybridisation programmes. Similar findings were also obtained from the previous studies (26).

Fruit characters

The 3 jointed pedicel varieties and 7 jointless pedicel genotypes showed a wide range of fruit characteristics (Table 2). The fruits' colour ranged from light red (4.66) to red (6.00) (Fig. 1), which may be attributed to differences in lycopene accumulation in the fruit skin. Similar observations were reported in a previous study (27). The fruits' visual quality varied from 4.33 to 7.66, while its texture varied from 0.12 N to 0.70 N. The fruit length recorded in the present investigation (3.83–7.53 cm) was higher than the range reported, where fruit lengths ranged from 3.20 to 6.40 cm in tomato genotypes under field conditions (28). Among the jointed pedicel varieties, Kashi Chayan recorded higher fruit width (5.43 cm) and maximum fruit juice yield (96.91 %). Among the jointless pedicel genotypes, the highest fruit width (5.93 cm), fruit weight (72.87 g), pericarp thickness (0.70 mm), firmness and juice yield (96.65 %) were recorded in EC605094, indicating its superior yield potential. Similarly, VRT 69 and EC695037 outperformed several jointed varieties in terms of fruit weight and size. The better performance of EC605094 might be attributed to the better genetic background for efficient assimilate partitioning and better fruit development. Similar associations of fruit size, firmness and yield-related traits in tomato were also reported (29). The fruit weight reported in this study (15.38–72.87 g) was comparatively higher than the range in previous studies. Research indicates that fruit weight ranging from (20–55 g) in traditional tomato varieties, which indicates the presence of genotypes with superior yield potential in the evaluated material (23). Kashi Chayan had the maximum fruit juice yield (96.91 %), followed by EC605094 with 96.65 %. The variation in the fruit characters may be due to genetic factors (30). Similarly, the pericarp thickness measured in the present study (0.30–0.70 mm) was relatively higher than in previous studies. Research indicates the

Table 1. Analysis of variance for 18 fruit and quality traits in tomato genotypes

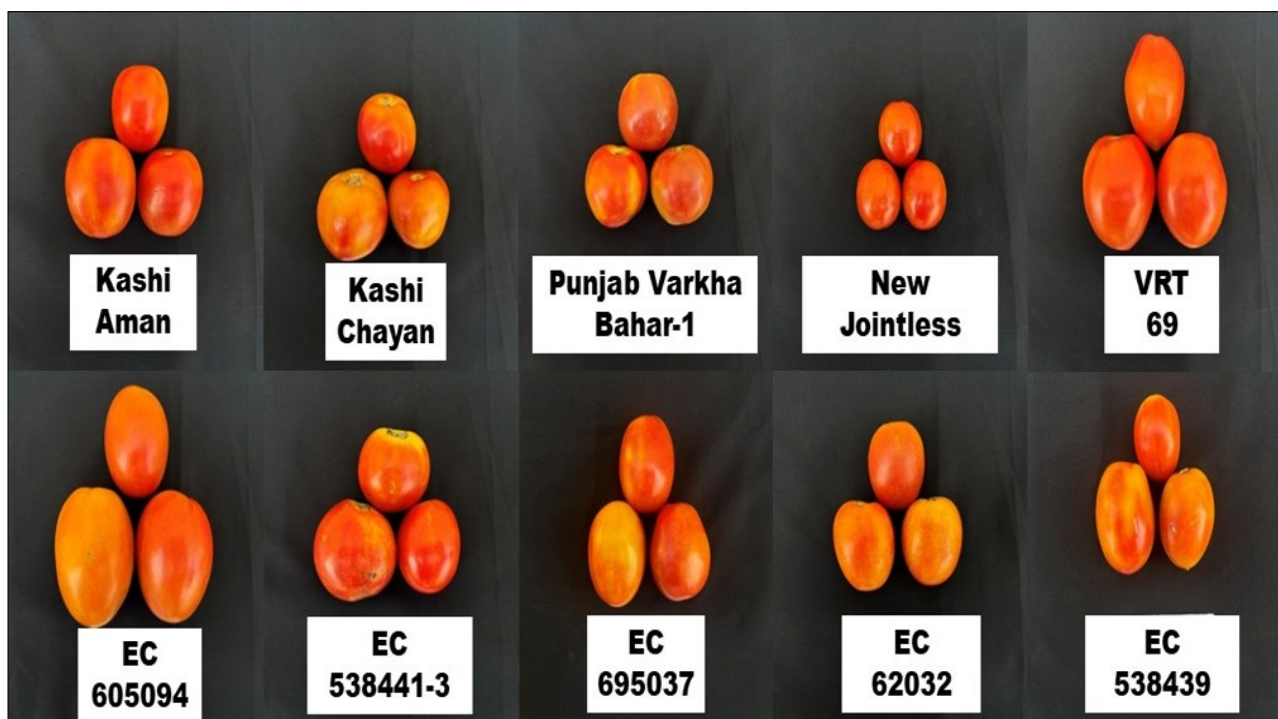
Traits	Mean sum of square		F value	Significance at 0.05 %
	Genotypes	Error		
df	9	20		
Fruit length (cm)	3.850	0.282	13.637	**
Fruit width (cm)	1.599	0.116	13.788	**
Fruit weight (g)	972.621	1.729	562.532	**
Number of seeds per fruit	4705.837	7.646	615.385	**
Number of locules per fruit	6.019	0.567	10.621	**
Pericarp thickness (mm)	0.043	0.012	3.583	**
Fruit texture (N)	0.161	0.008	19.795	**
Fruit juice yield (%)	53.002	15.920	3.329	**
Visual quality	8.000	1.333	6.000	**
Fruit colour	0.874	0.200	4.370	**
pH	0.078	0.054	1.443	NA
Total Soluble Solids (°B)	0.774	0.044	17.725	**
Total sugars (%)	2.253	1.018	2.213	NA
Titrateable acidity (%)	0.008	0.001	10.478	**
Ascorbic acid (mg/100 g)	251.630	1.393	180.600	**
Lycopene (mg/100 g)	15.019	3.859	3.891	**
β- Carotene (mg/100 g)	12.145	3.457	3.514	**
Sugar- acid ratio	299.371	7.711	38.824	**

df: Degrees of freedom; NA: Non-significant.

Table 2. Fruit morphological characterisation of tomato genotypes

Tomato genotypes	FL (cm)	FW (cm)	FWT (g)	NSPF	NLPF	PT (mm)	FT (N)	FJY (%)	VQ	FC
G ₁	4.67 ^{ef}	4.73 ^{de}	57.35 ^d	157.33 ^c	3.00 ^{bc}	0.43 ^{bcd}	0.63 ^{ab}	91.32 ^{abc}	6.33 ^a	5.66 ^{ab}
G ₂	4.60 ^{ef}	5.43 ^{abc}	52.66 ^e	232.00 ^a	6.00 ^a	0.30 ^d	0.55 ^{abc}	96.91 ^a	3.67 ^{cd}	6.00 ^a
G ₃	4.46 ^{ef}	4.93 ^{cd}	41.23 ^g	153.66 ^c	5.33 ^a	0.56 ^{ab}	0.70 ^a	95.44 ^a	2.33 ^d	6.00 ^a
G ₄	3.83 ^f	3.40 ^f	15.38 ⁱ	164.00 ^b	3.00 ^{bc}	0.50 ^{bc}	0.12 ^d	91.69 ^{abc}	2.33 ^d	5.66 ^{ab}
G ₅	6.56 ^b	5.53 ^{ab}	61.38 ^c	101.00 ^f	2.66 ^{bc}	0.46 ^{bcd}	0.45 ^c	93.59 ^{ab}	5.66 ^{ab}	4.66 ^c
G ₆	7.53 ^a	5.93 ^a	72.87 ^a	116.33 ^e	2.33 ^{bc}	0.70 ^a	0.70 ^a	96.66 ^a	6.33 ^a	5.33 ^{abc}
G ₇	4.86 ^{de}	4.96 ^{bcd}	46.05 ^f	138.33 ^d	5.00 ^a	0.46 ^{bcd}	0.50 ^{bc}	92.75 ^{ab}	2.33 ^d	5.00 ^{bc}
G ₈	6.13 ^{bc}	5.03 ^{bcd}	64.72 ^b	119.00 ^e	3.33 ^b	0.53 ^{ab}	0.67 ^a	89.26 ^{abc}	5.67 ^{ab}	4.66 ^c
G ₉	4.80 ^{de}	4.33 ^e	38.36 ^h	116.66 ^e	2.00 ^c	0.60 ^{ab}	0.14 ^d	86.33 ^{bc}	4.33 ^{bc}	4.66 ^c
G ₁₀	5.60 ^{cd}	4.23 ^e	25.03 ⁱ	101.00 ^f	2.33 ^{bc}	0.33 ^{cd}	0.19 ^d	84.36 ^c	4.33 ^{bc}	5.00 ^{bc}
SE(d)	0.434	0.278	1.074	2.258	0.615	0.089	0.074	3.260	0.940	0.365
C.D. (p = 0.05)	0.911	0.584	2.255	4.743	1.291	0.188	0.155	6.800	1.970	0.767

Means with different superscript letters are statistically different at $p < 0.05$ based on Duncans' multiple range test (DMRT); SE(d): standard error of a difference; C.D.: Critical difference; G₁: Kashi Aman; G₂: Kashi Chayan; G₃: Punjab Varkha Bahar-1; G₄: New Jointless; G₅: VRT 69; G₆: EC605094; G₇: EC 538441-3; G₈: EC695037; G₉: EC62032; G₁₀: EC538439; FL: fruit length (cm); FW: fruit width (cm); FWT: fruit weight (g); NSPF: number of seeds per fruit; NLPF: number of locules per fruit; PT: pericarp thickness (mm); FT: fruit texture (N); VQ: visual quality; FC: fruit colour; TSS: total soluble solids (°B); TS: total sugars (%); TA: titrateable acidity (%); AA: ascorbic acid (mg/100 g); LYC: lycopene (mg/100 g); BC: β-carotene (mg/100 g); SAR: sugar- acid ratio.

**Fig. 1.** Fruit morphological variation of ten tomato genotypes.

potential of the evaluated genotypes for improved firmness and shelf life (31). In the current study, the number of seeds per fruit ranged between 101.00 and 232.00, while the number of locules per fruit varied from 2.00–6.00. The observed variation in the number of seeds and locules per fruit may be attributed to genetic differences among the genotypes. Similar results were previously reported in tomato (29, 32).

Quality characters

In the present study, the pH of tomato fruit varied from 4.39–4.90 (Fig. 2a). Among the jointless pedicel genotypes, the highest pH content was observed in EC695037 (4.90), followed by EC605094 (4.82), whereas in the jointed pedicel variety, Punjab Varkha Bahar-1 attained the highest pH content. Total soluble solids are a crucial determinant of quality and shelf life. Additionally, tomato taste and consistency are significantly impacted by TSS levels (33). In the current study, TSS of tomato genotypes varied from 4.31–5.76 °B (Fig. 2b), which were also in agreement with the reported value, indicating uniformity in fruit quality traits of tomato germplasm (32). In addition, total sugars in tomatoes are another factor that affects the fruits' quality, which controls its sweetness and flavour. EC605094 had the highest total sugar levels (4.15 %), followed by New Jointless (3.95 %) (Fig. 2c). In the present study, EC62032 had recorded the lowest titratable acidity (0.124 %), whereas Kashi Chayan had the highest (0.31 %) (Fig. 2d). The wide range in the tomato fruits' acidity and total sugars could be the cause of the difference in the sugar–acid ratio. Research indicates that the range of titratable acidity levels was 0.30–0.73 % (32). In case of ascorbic acid content, New Jointless had recorded the highest (45.91 mg/100 g), followed by EC538439 (41.27 mg/100 g), while

EC538441-3 had the lowest (15.94 mg/100 g) (Fig. 3a). The higher ascorbic acid content observed in New Jointless may be attributed to the higher genetic potential for the biosynthesis and accumulation of antioxidants during the fruit development and ripening. Research indicates that similar observations were made regarding variability in ascorbic acid content in tomato genotypes (34, 35). In the current investigation, the lycopene and β -carotene content greatly varied across the tomato genotypes (Fig. 3b and c), with New Jointless having the highest level (11.96 mg/100 g and 11.56 mg/100 g), followed by Kashi Chayan (10.19 mg/100 g and 9.83 mg/100 g), respectively. Among the jointed pedicel varieties, Kashi Chayan exhibited higher lycopene and β -carotene contents compared to other jointed varieties. However, among the jointless pedicel genotypes, New Jointless showed the highest ascorbic acid, lycopene and β -carotene contents, indicating superior antioxidant potential. The improved nutritional quality of New Jointless may be associated with enhanced carotenoid biosynthesis and accumulation during fruit ripening. The intense red fruit colour of this genotype also supports higher pigment accumulation. Similar relationships between tomato fruit colour and carotenoid accumulation have been reported (7, 27). Significant variation was also seen in the sugar–acid ratio (Fig. 3d), with the highest ratio found in EC695037 (31.14) and the lowest in VRT 69 (6.48). The variations in sugar–acid ratio could be caused by environmental factors or genetic variation within the genotypes (36). The overall results indicated the jointless pedicel genotypes had a considerable potential for improvement of nutritional and processing quality traits in tomato breeding programmes.

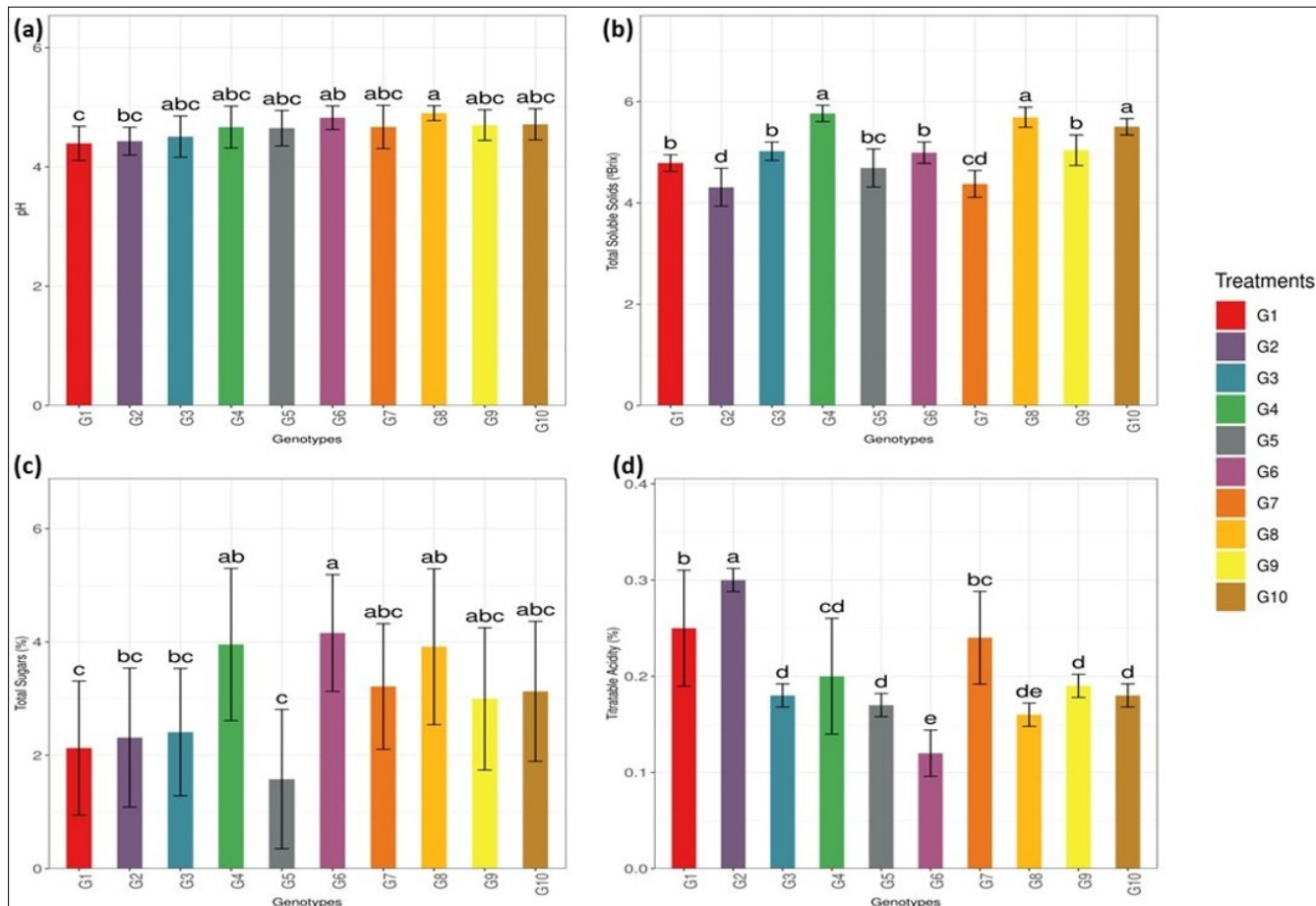


Fig. 2. Quality attributes of 10 tomato genotypes. a: pH; b: total soluble solids (TSS); c: total sugars; d: titratable acidity. G₁: Kashi Aman; G₂: Kashi Chayan; G₃: Punjab Varkha Bahar-1; G₄: New Jointless; G₅: VRT 69; G₆: EC605094; G₇: EC538441-3; G₈: EC695037; G₉: EC62032; G₁₀: EC538439.

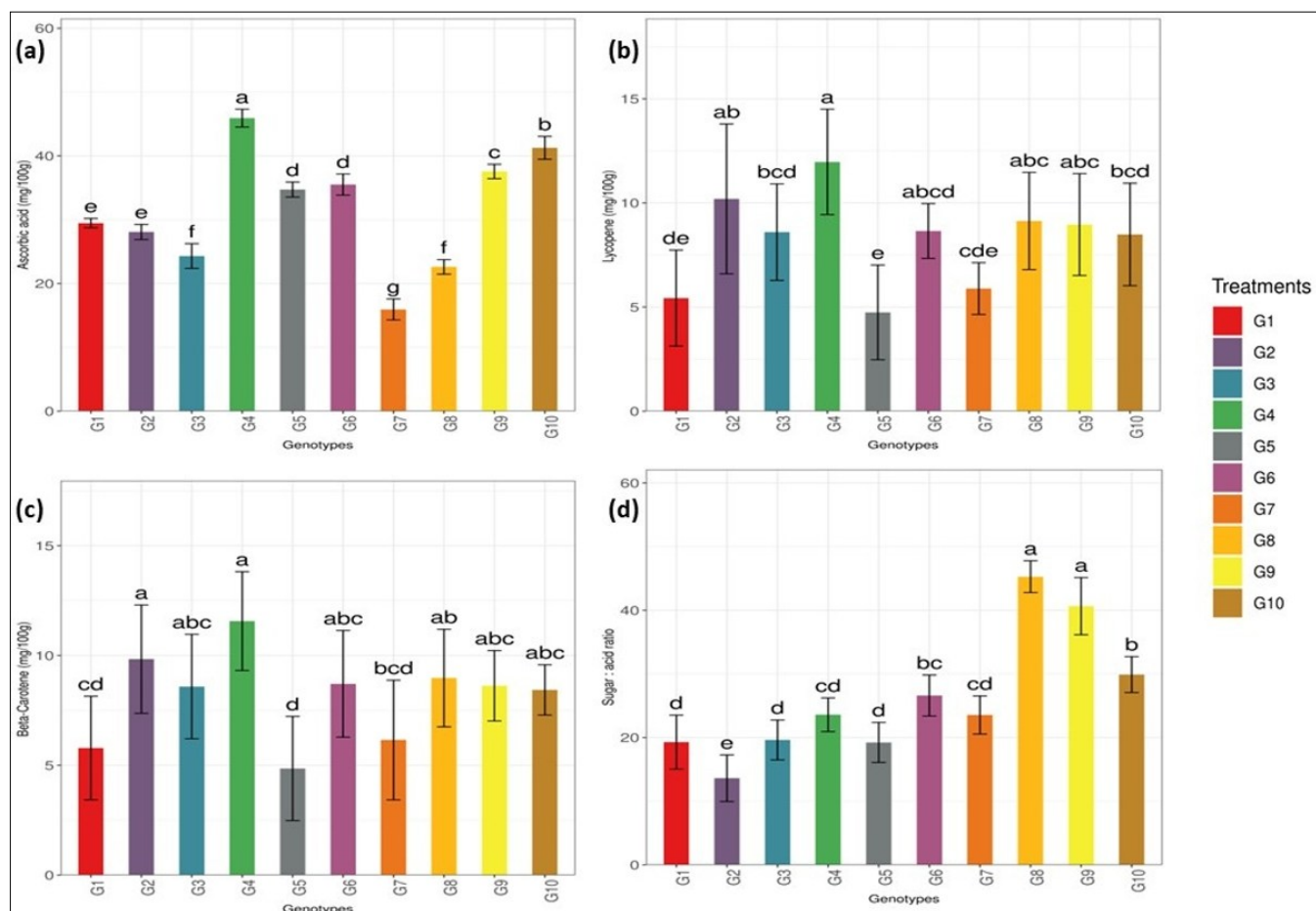


Fig. 3. Quality attributes of 10 tomato genotypes. a: ascorbic acid; b: Lycopene; c: β - carotene; d: sugar- acid ratio. G₁: Kashi Aman; G₂: Kashi Chayan; G₃: Punjab Varkha Bahar-1; G₄: New Jointless; G₅: VRT 69; G₆: EC605094; G₇: EC538441-3; G₈: EC695037; G₉: EC 62032; G₁₀: EC538439.

Genetic variability analysis

The degree of diversity in a population has a significant impact on the success of selection. The phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) are important indices for assessing this variability. The overall variance observed in a population is due to both genetic and environmental factors. In the present study, the traits including fruit texture (PCV: 51.69; GCV: 48.06), number of locules per fruit (PCV: 44.12; GCV: 38.52), fruit weight (PCV: 37.97; GCV: 37.87), sugar-acid ratio (PCV: 39.21; GCV: 37.74), visual quality (PCV: 43.51; GCV: 34.40), ascorbic acid (PCV: 29.20; GCV: 28.96), number of seeds per fruit (PCV: 28.35; GCV: 28.28), titratable acidity (PCV: 29.01; GCV: 24.27), lycopene (PCV: 33.55; GCV: 23.51), total sugars (PCV: 40.12; GCV: 21.53), β -carotene (PCV: 30.92; GCV: 20.88), pericarp thickness (PCV: 30.50; GCV: 20.75) and fruit length (PCV: 22.86; GCV: 20.55) exhibited high GCV, indicating significant genetic variability that can be effectively utilised through selection (Table 3). The traits such as fruit width (PCV: 16.10; GCV: 14.49) exhibited moderate GCV, indicating that while genetic variability is present, improvement through selection is possible; however, expected genetic gain may be comparatively slower than that of traits with high GCV. Traits such as pH (PCV: 5.36; GCV: 1.92), fruit juice yield (PCV: 5.79; GCV: 3.83), fruit colour (PCV: 12.37; GCV: 9.00) and TSS (PCV: 10.68; GCV: 9.83) demonstrated low GCV, indicating limited genetic diversity. Similar results were previously reported in various crops (37). GCV and PCV exhibit minimal variation across most variables, indicating a diminished environmental impact. The minor differences between PCV and GCV indicate that a heritable component is essential for their expression and the selection of genotypes.

Heritability refers to the extent to which traits are passed on from genotypes to their progeny. Traits with high heritability are less influenced by environmental influences and may be directly enhanced through the selection process (38). This study calculated heritability in the broad sense, encompassing both additive and non-additive genetic variance. The examined characteristics demonstrated heritability, varying from 12.90 % for pH to 99.50 % for fruit weight and number of seeds per fruit (Table 3). The characteristics pH (12.90 %) and total sugars (28.80 %) demonstrated low heritability, while β -carotene (45.60 %), pericarp thickness (46.30 %), lycopene (49.10 %) and fruit colour (52.90 %) displayed moderate heritability. The traits including fruit weight (99.50 %), number of seeds per fruit (99.50 %), ascorbic acid (98.40 %), sugar-acid ratio (92.70 %), fruit texture (86.40 %), total soluble solids (84.70 %), fruit width (81.00 %), fruit length (80.80 %), number of locules per fruit (76.20 %), titratable acidity (70.00 %) and visual quality (62.50 %) demonstrated high heritability, indicating that these traits are predominantly controlled by genetic factors with limited environmental impact.

Nevertheless, heritability estimates alone are insufficient for assessing genetic improvement and must be evaluated in combination with genetic advance as a percentage of the mean (39). This study revealed that traits like fruit weight (heritability: 99.50; GAM: 77.80), sugar-acid ratio (heritability: 92.70; GAM: 74.83), the number of locules per fruit (heritability: 99.50; GAM: 58.12) and ascorbic acid (heritability: 98.40; GAM: 59.16) exhibited high heritability coupled with high GAM, indicating the predominance of additive gene action (Table 3). This suggests that these traits are primarily governed by additive genes and that direct selection for their improvement would be effective.

Table 3. Genetic variability analysis for 18 characters in 10 tomato genotypes

Traits	Phenotypic coefficient of variation (PCV)	genotypic coefficient of variation (GCV)	Heritability (%)	Genetic advance value % means (GAM)
FL	22.86	20.55	80.80	38.06
FW	16.10	14.49	81.00	26.86
FWT	37.97	37.87	99.50	77.80
NSPF	28.35	28.28	99.50	58.12
NLPF	44.12	38.52	76.20	69.27
PT	30.50	20.75	46.30	29.07
FT	51.69	48.06	86.40	92.05
FJY	5.79	3.83	43.70	5.21
VQ	43.51	34.40	62.50	56.03
FC	12.37	9.00	52.90	13.48
pH	5.36	1.92	12.90	1.425
TSS	10.68	9.83	84.70	18.64
TS	40.12	21.53	28.80	23.80
TA	29.01	24.27	70.00	41.84
AA	29.20	28.96	98.40	59.16
LYC	33.55	23.51	49.10	33.92
BC	30.92	20.88	45.60	29.04
SAR	39.21	37.74	92.70	74.83

FL: fruit length (cm); FW: fruit width (cm); FWT: fruit weight (g); NSPF: number of seeds per fruit; NLPF: number of locules per fruit; PT: pericarp thickness (mm); FT: fruit texture (N); VQ: visual quality; FC: fruit colour; TSS: total soluble solids ($^{\circ}$ B); TS: total sugars (%); TA: titratable acid (%); AA: ascorbic acid (mg/100 g); LYC: lycopene (mg/100 g); BC: β -carotene (mg/100 g); SAR: sugar- acid ratio.

Pearsons' correlation analysis

Understanding correlations among fruit, yield and quality traits is essential for effective selection and hybridisation programs, as these relationships help breeders identify traits that simultaneously improve yield and fruit quality (40). In the present study, strong positive correlations were observed among fruit characters (Fig. 4). Fruit length showed positive correlations with fruit width ($r = 0.70$), fruit weight ($r = 0.71$), pericarp thickness ($r = 0.38$), fruit texture ($r = 0.37$), visual quality ($r = 0.72$) and pH ($r = 0.60$). Fruit width also exhibited strong positive correlations with fruit weight ($r = 0.90$), fruit texture ($r = 0.77$), fruit juice yield ($r = 0.62$) and visual quality ($r = 0.48$). Similarly, fruit weight showed positive associations with fruit texture ($r = 0.80$) and visual quality ($r = 0.71$), indicating that larger fruits tend to possess better firmness and appearance. The number of locules per fruit showed positive correlations with fruit texture ($r = 0.44$), visual quality ($r = 0.58$), fruit colour (FC) ($r = 0.60$) and titratable acidity (TA) ($r = 0.63$). Pericarp thickness was positively associated with pH ($r = 0.50$) and total sugars ($r = 0.46$), suggesting that thicker pericarp fruits may contribute to better taste and structural stability. The quality traits also exhibited strong interrelationships. Total soluble solids showed positive correlations with pH ($r = 0.56$), total sugars ($r = 0.60$), lycopene ($r = 0.53$), β -carotene ($r = 0.54$) and sugar-acid ratio ($r = 0.60$). Total sugars were also positively correlated with pH ($r = 0.73$), lycopene ($r = 0.59$), β -carotene ($r = 0.61$) and sugar-acid ratio ($r = 0.56$), indicating that higher sugar accumulation contributes to improved fruit quality and flavour. Negative correlations were also observed. The number of seeds per fruit and number of locules per fruit showed negative correlations with some fruit size and quality traits. Titratable acidity exhibited strong negative correlations with fruit length ($r = -0.67$), pericarp thickness ($r = -0.72$), pH ($r = -0.76$), TSS ($r = -0.56$) and total sugars ($r = -0.45$). Similar results were previously reported in various crops (41, 42). Based on these findings, fruit characters are strongly interrelated and positively associated with texture and visual quality, while biochemical quality traits such as sugars, pigments and sugar-acid ratio are positively correlated, providing useful selection criteria for improving fruit yield and quality.

Principal component analysis (PCA)

In the present study, nine principal components (PCs) were used to distribute the diversity within the tomato genotypes. Four of these nine PCs had eigenvalues greater than one, which together accounted for 86.39 % of the diversity in fruit and quality characteristics across the ten tomato genotypes (Table 4). PC1 recorded the highest eigenvalue of 6.26, contributing 34.77 % of the total variation, followed by PC2 with an eigenvalue of 5.25, contributing 29.19 % variation. PC3 and PC4 explained 14.64 % and 7.80 % of the total variation, respectively (Table 4). The high value of the cumulative variance explained by the first four principal components indicates that there exists a significant genetic diversity among the studied tomato genotypes and that the four principal components represent a good proportion of the variation among the evaluated traits. This suggests that the genotypes were significantly influenced by the characteristics found within these components. Similar results were noticed in the previous findings (43, 44).

In a scree plot graph, the proportion of variance attributable to each component was represented by plotting the eigenvalues of each factor in descending order against the number of primary components. The scree plot showed that the remaining PCs showed very little fluctuation, except for the first four principal components (Fig. 5). It was evident from the scree plot that PC1 had the highest degree of variance, indicating that suggesting the efficacy of genotype selection based on PC1 characteristics. The first principal component (PC1) characteristics like number of seeds per plant (10.59), number of locules per fruit (11.21), TSS (11.88), titratable acidity (10.41), sugar-acid ratio (10.65), total sugars (8.54), pH (8.15) and visual quality (6.15) contributed most significantly to the divergence (Table 5). Whereas, in the second principal component (PC2), characters such as fruit weight (16.06), fruit width (14.69), fruit length (11.19), lycopene (10.10), β -carotene (9.96), fruit texture (9.43) and fruit colour (8.49) were important contributors (Table 5). Similarly, the main factors that contributed to PC3 were β - carotene (14.81), fruit juice yield (14.02), lycopene (13.69), visual quality (12.31), pericarp thickness (9.03) and fruit texture (8.03) (Table 5). As for the

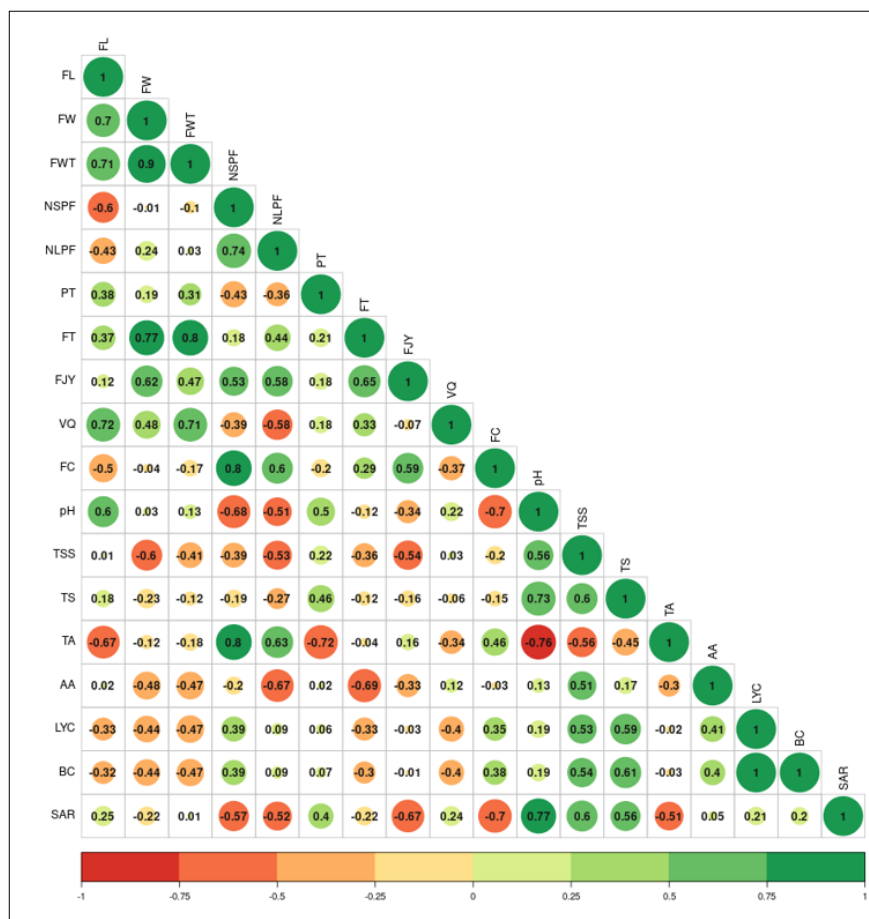


Fig. 4. Correlogram showing the relationship among 18 traits of tomato genotypes. FL: fruit length (cm); FW: fruit width (cm); FWT: fruit weight (g); NSPF: number of seeds per fruit; NLPF: number of locules per fruit; PT: pericarp thickness (mm); FT: fruit texture (N); VQ: visual quality; FC: fruit colour; TSS: total soluble solids ($^{\circ}$ B); TS: total sugars (%); TA: titratable acidity (%); AA: ascorbic acid (mg/100 g); LYC: lycopene (mg/100 g); BC: β -carotene (mg/100 g); SAR: sugar- acid ratio.

Table 4. Eigenvalues, variance and cumulative variability towards principal components

Principal component	Eigen value	Percentage of variance	Cumulative percentage of variance
PC1	6.26	34.77	34.77
PC2	5.25	29.19	63.96
PC3	2.63	14.64	78.60
PC4	1.40	7.80	86.39
PC5	0.93	5.15	91.55
PC6	0.63	3.52	95.06
PC7	0.47	2.62	97.68
PC8	0.29	1.59	99.28
PC9	0.13	0.72	100

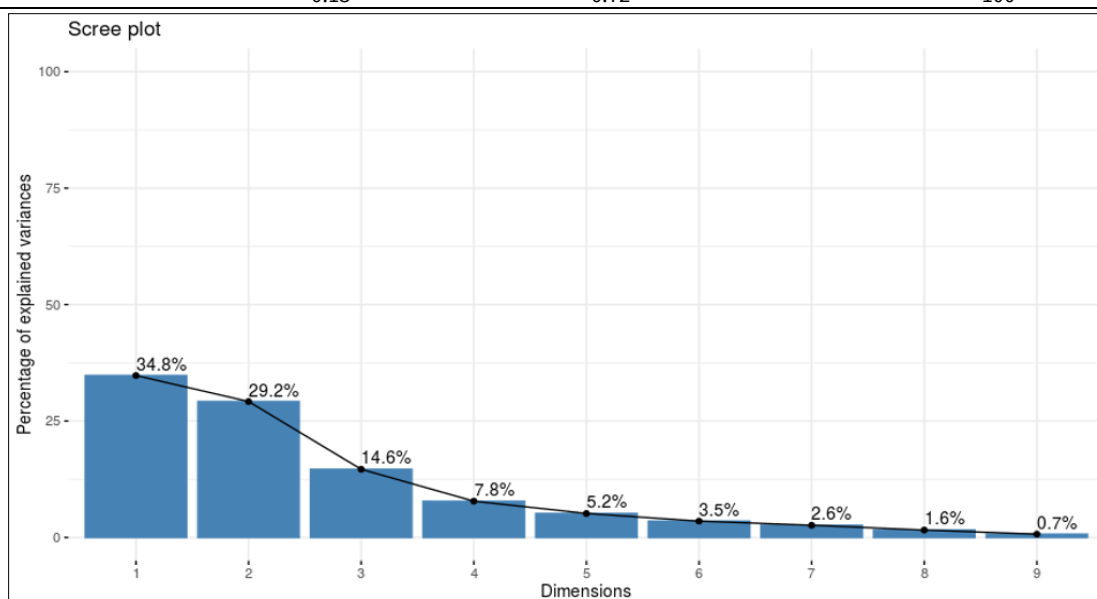


Fig. 5. Scree plot for nine values and cumulative variability explained by principal components in tomato genotypes.

Table 5. Factor loadings of fruit morphology and quality traits for the first four major principal components (PCs)

Variables	PC1	PC2	PC3	PC4
Fruit length (cm)	3.61	11.19	1.11	3.17
Fruit width (cm)	0.95	14.69	2.94	0.30
Fruit weight (g)	0.07	16.06	2.51	0.11
Number of seeds per fruit	10.59	2.43	3.72	0.31
Number of locules per fruit	11.21	0.09	3.50	11.01
Pericarp thickness (mm)	3.86	1.69	9.03	0.03
Fruit texture (N)	2.23	9.43	8.03	0.73
Fruit juice yield (%)	5.71	1.23	14.02	2.39
Visual quality	6.15	2.33	12.31	3.99
Fruit colour	1.93	8.49	0.43	11.57
pH	8.15	2.08	6.10	7.80
Total Soluble Solids (^o Brix)	11.88	0.44	3.12	4.75
Total sugars (%)	8.54	3.97	1.24	0.23
Titrateable acidity (%)	10.41	1.61	2.55	1.62
Ascorbic acid (mg/100 g)	3.34	4.21	0.73	37.56
Lycopene (mg/100 g)	0.38	10.10	13.69	0.56
β- Carotene (mg/100 g)	0.35	9.96	14.81	0.57
Sugar- acid ratio	10.65	0.008	0.14	13.29

fourth principal component (PC4), the primary components such as ascorbic acid (37.56), sugar–acid ratio (13.29), fruit colour (11.57) and number of locules per fruit (11.01) were the main factors that contributed (Table 5). Similar results were previously reported in various crops (45, 46). The contribution of the individual trait in the first 8 major principal components was shown in (Fig. 6).

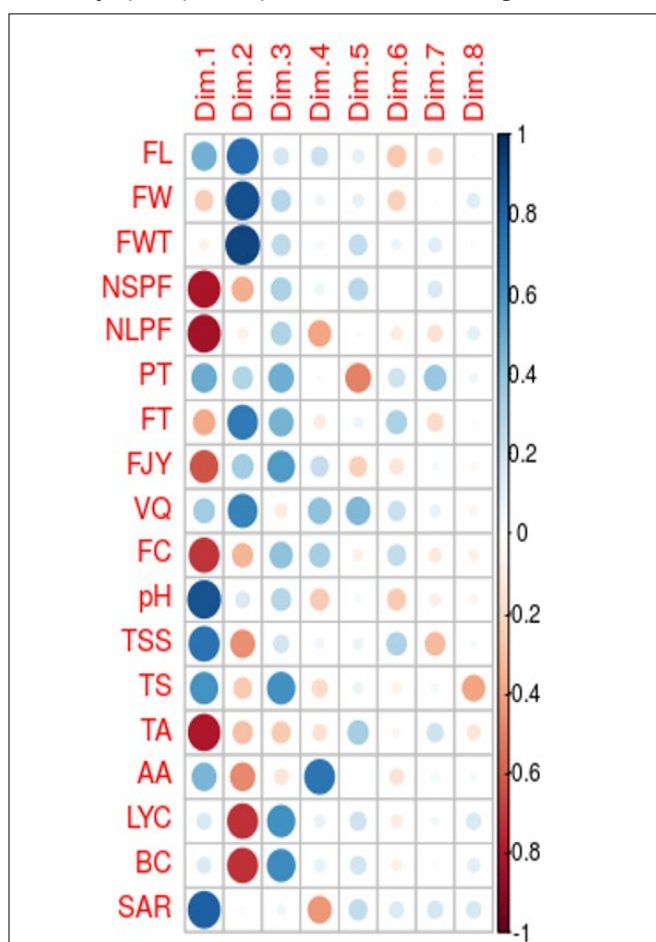


Fig. 6. Contribution on the individual trait in first 8 major principal components. FL: fruit length (cm); FW: fruit width (cm); FWT: fruit weight (g); NSPF: number of seeds per fruit; NLPF: number of locules per fruit; PT: pericarp thickness (mm); FT: fruit texture (N); VQ: visual quality; FC: fruit colour; TSS: total soluble solids (^oB); TS: total sugars (%); TA: titrateable acidity (%); AA: ascorbic acid (mg/100 g); LYC: lycopene (mg/100 g); BC: β-carotene (mg/100 g); SAR: sugar- acid ratio.

The first two principal components (PC1 and PC2), explaining 63.96 % of total variability, were used to illustrate relationships among tomato genotypes through a PCA biplot combining genotypes and traits (Fig. 7). Vector length indicates contribution to divergence, with fruit weight contributing most, followed by fruit width, titrateable acidity, pH, fruit length and TSS (47). Strong positive associations were observed among lycopene, β-carotene and ascorbic acid, as their vectors formed acute angles, indicating that genotypes rich in one tend to be rich in the others. Genotypes EC62032 and EC538439, positioned on the positive side of PC1, are linked to superior nutritional quality, including higher lycopene, β-carotene and TSS. The TSS, pH and sugar–acid ratio also showed positive correlation, contributing to improved sweetness and flavour. Pericarp thickness and fruit texture were weakly related, as indicated by near-perpendicular vectors. Genotypes VRT 69 and EC538441-3 on the positive PC2 axis were associated with favourable morphological traits. Negative correlations between pH, sugar–acid ratio and titrateable acidity aligned with fruit quality (48). The wide distribution of genotypes showed high diversity, which is beneficial for effective selection in tomato breeding programmes. However, the current study was performed under a single environment with a limited number of genotypes. Therefore, multi-season evaluations are needed to validate the stability, adaptability and performance of these genotypes before their utilisation in large-scale breeding programmes.

Conclusion

The evaluation of tomato genotypes revealed significant genetic variability for fruit and quality traits, indicating a great potential for tomato improvement through selection and hybridisation. Among the jointless pedicel genotypes, EC605094 exhibited superior performance for fruit characters, whereas New Jointless recorded the highest antioxidant potential through elevated lycopene, β-carotene and ascorbic acid contents. Among the jointed pedicel varieties, Kashi Chayan showed desirable fruit quality traits, including higher juice yield and carotenoid content. High heritability coupled with high genetic advance for important traits like fruit weight, sugar-acid ratio, number of locules per fruit and ascorbic acid indicated predominance of additive gene action, suggesting effectiveness of direct selection. Correlation and principal component analyses (PCA) further revealed that fruit weight, fruit size and biochemical parameters were the main contributors to genetic divergence and confirmed the strong association among

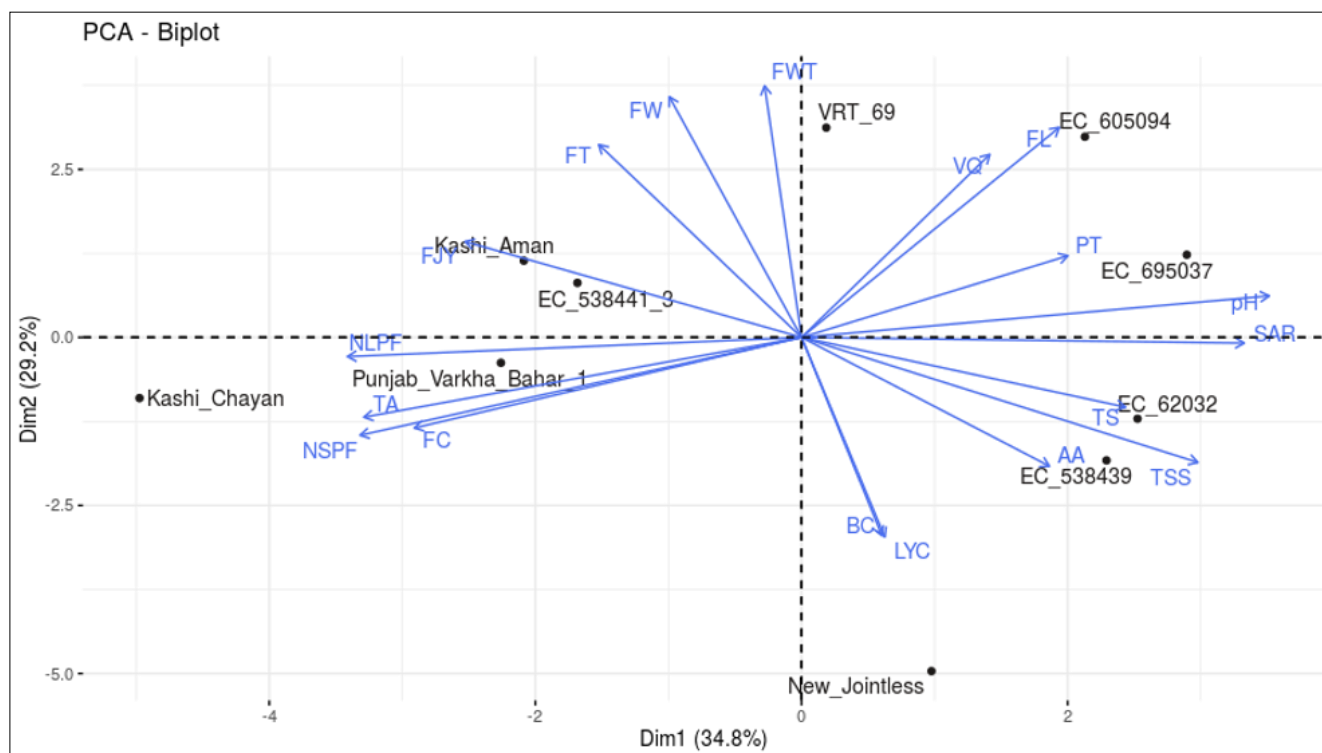


Fig. 7. Principal component analysis (PCA) biplot between PC1 (34.8 %) and PC2 (29.2 %) scores of tomato genotypes and its variables. FL: fruit length (cm); FW: fruit width (cm); FWT: fruit weight (g); NSPF: number of seeds per fruit; NLPF: number of locules per fruit; PT: pericarp thickness (mm); FT: fruit texture (N); VQ: visual quality; FC: fruit colour; TSS: total soluble solids (°B); TS: total sugars (%); TA: titratable acidity (%); AA: ascorbic acid (mg/100 g); LYC: lycopene (mg/100 g); BC: β -carotene (mg/100 g); SAR: sugar-acid ratio.

fruit yield and quality traits. From a practical breeding perspective, the jointless pedicel genotypes EC605094, EC695037, VRT 69 and New Jointless, along with the jointed variety Kashi Chayan, may serve as promising parental lines for future hybridisation programmes aimed at developing high-yielding tomato hybrids with improved nutritional quality and adaptability under present climatic conditions. However, further multi-season evaluations are required to validate the stability and wider adaptability of these genotypes before their commercial utilisation in tomato breeding programmes.

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Authors' contributions

KRA contributed to conceptualisation, methodology development, investigation, validation, visualisation, formal analysis, manuscript drafting and review and editing. JKT and RV contributed to conceptualisation, methodology development, investigation, validation, visualisation, formal analysis, review and editing and supervision. AD, SN and GS contributed to review and editing of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the authors used QuillBot v32.1.3 in order to enhance the language and grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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