

UNRAVELLING FRUIT TRAIT DIVERSITY AND BREEDING POTENTIAL IN TOMATO VARITOME ASSOCIATION PANEL ACROSS TWO SEASONS

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ABSTRACT

Genetic variability in tomato germplasm provides opportunities to identify accessions for the improvement of fruit morphology, quality and productivity. This study assessed variability and selection potential for ten flowering, fruit and yield traits in 137 accessions of the tomato Varitome collection, comprising 25 *Solanum pimpinellifolium*, 93 *S. lycopersicum* var. *cerasiforme* and 19 *S. lycopersicum* var. *lycopersicum* accessions, during Summer 2025 and Rabi 2025–26 at ICAR–NISST Regional Station, Bengaluru, India. Each season was laid out in an augmented randomized complete block design with four blocks and six replicated checks, and analysed separately. Test accessions differed significantly for all traits in both seasons, except fruit yield per plant in Rabi. Average fruit weight ranged from 1.11 to 146.91 g in Summer and from 1.18 to 149.78 g in Rabi (means 26.00 ± 3.15 and 26.83 ± 3.21 g) and recorded the highest genotypic coefficient of variation (124.99 and 123.27%) with high broad-sense heritability (97.78 and 94.14%). Locule number, fruit equatorial diameter and fruit height combined high genotypic variability with heritability above 90% and high genetic advance as per cent of mean in both seasons. Total soluble solids averaged 6.80 and 6.85 °Brix, with heritability of 91.71 and 92.06%. Heritability of fruit yield per plant declined from 68.26% in Summer to 47.34% in Rabi, indicating weaker support for phenotypic selection for yield in the latter season. Fruit weight, locule number, fruit dimensions and soluble solids are therefore effective criteria for preliminary selection within the panel. Because broad-sense heritability does not partition additive genetic variance and the seasons were analysed separately, selected accessions require replicated multi-environment evaluation to confirm their stability and breeding value.

KEYWORDS: Tomato; Varitome; Genetic variability; Broad-sense heritability; Genetic advance; Fruit quality; Augmented design

INTRODUCTION

Genetic improvement of tomato (*Solanum lycopersicum* L.) depends on the identification and use of germplasm carrying desirable variation for fruit morphology, quality and productivity. Fruit weight, polar and equatorial diameters, locule number and pericarp thickness determine the diversity of fruit types, whereas total soluble solids and pH are important quality attributes. Selection priorities vary with the intended use of the crop, requiring breeders to identify accessions with suitable combinations of traits. Evaluations of tomato landraces and heirloom collections have demonstrated considerable variation in fruit characteristics, providing opportunities to identify donors for breeding programmes (Farinon et al., 2022; Tripodi et al., 2023). Systematic germplasm characterization is therefore essential for translating available diversity into useful selection material. The diversity of tomato fruit characteristics reflects the effects of domestication, geographical differentiation and subsequent selection. Lin et al. (2014) demonstrated that domestication and improvement involved partly distinct sets of genomic regions associated with increased fruit size. Collections encompassing wild relatives, cherry-type accessions and cultivated tomatoes therefore provide opportunities to examine variation across different genetic backgrounds. Zhou et al. (2015) documented substantial morphological and molecular diversity among cultivated tomatoes, wild relatives and introgression lines, highlighting the value of these resources for genetic studies. However, differences among taxonomic groups can contribute substantially to variation within a mixed germplasm panel, and estimates obtained from such collections should be interpreted in relation to their genetic composition rather than assumed to represent variation within a single breeding population.

The Varitome collection provides a resource for investigating this diversity. Mata-Nicolás et al. (2020) characterized 163 accessions representing *S. pimpinellifolium*, *S. lycopersicum* var. *cerasiforme* and *S. lycopersicum* var. *lycopersicum*, selected to capture genetic and morphological variation from the centres of tomato origin and domestication, and documented extensive variation in fruit, floral and vegetative characteristics. Evaluation of accessions from this resource under additional growing conditions can extend its practical value by determining how quantitative traits are expressed in environments relevant to breeding

programmes. Assessment of the Varitome panel at Bengaluru therefore provides complementary information for identifying accessions with desirable fruit characteristics under local seasonal conditions.

Effective selection requires consideration of both the magnitude of variability and the relative contributions of genetic and environmental effects to trait expression. Genotypic and phenotypic coefficients of variation express variability relative to the trait mean, facilitating comparisons among characters measured in different units, while broad-sense heritability indicates the proportion of phenotypic variance attributable to genotypic differences under the specified experimental conditions (Burton and DeVane, 1953; Johnson et al., 1955). Heritability depends on the population, environment, experimental design and unit of selection and is not a fixed property of a character (Holland et al., 2003). High broad-sense heritability can support preliminary selection among accessions, but it does not by itself establish the predominance of additive gene action or predict progeny performance. Previous investigations have shown that tomato traits differ in their levels of variability and heritability. Farinon et al. (2022) reported considerable diversity in fruit weight, locule number, fruit shape, soluble solids and yield among tomato germplasm from central Italy, and Tripodi et al. (2023), evaluating 60 heirloom accessions over two seasons, reported trait-dependent heritability, with higher estimates for fruit weight than for soluble solids. Yogendra and Ramanjini Gowda (2013) further demonstrated segregation for fruit firmness and shelf life in progenies derived from crosses involving ripening mutants, illustrating the importance of evaluating specific quality attributes alongside agronomic performance.

Although the morphological diversity of the Varitome collection has been established, its use in a particular breeding programme requires evaluation under the relevant production conditions. Assessment across two seasons provides an opportunity to compare trait distributions and season-specific genetic parameters within the same panel. The present study therefore aimed to (i) quantify the variability among 137 Varitome accessions for ten flowering, fruit morphology, fruit quality and yield traits during Summer 2025 and Rabi 2025–26 at Bengaluru, India; (ii) estimate season-specific genotypic and phenotypic coefficients of variation, broad-sense heritability and expected genetic advance; and (iii) identify traits that offer the greatest scope for preliminary accession selection and subsequent replicated evaluation.

MATERIALS AND METHODS

Plant material and experimental site

The investigation was conducted at the ICAR–National Institute of Seed Science and Technology, Regional Station, GKVK campus, Bengaluru, Karnataka, India (13.0886° N, 77.5772° E) during Summer 2025 and Rabi 2025–26. The experimental material comprised 137 tomato Varitome accessions obtained from the C. M. Rick Tomato Genetics Resource Center, University of California, Davis, USA. The panel included 25 accessions of *Solanum pimpinellifolium* (SP), 93 of *S. lycopersicum* var. *cerasiforme* (SLC) and 19 of *S. lycopersicum* var. *lycopersicum* (SLL), representing diverse genetic backgrounds and fruit characteristics associated with tomato domestication and diversification (Mata-Nicolás et al., 2020). Six checks, namely Sahoo, Meghdoot, TO-6242, Abhilash, US400 and Champ33, were included, giving 143 entries (137 test accessions and six checks) in each season (Table 1).

Table 1. Details of the tomato Varitome association panel and the field evaluation in two seasons

Characteristic	Summer 2025	Rabi 2025–26
Test accessions (SP / SLC / SLL)	137 (25 / 93 / 19)	137 (25 / 93 / 19)
Check entries	6	6
Total entries per season	143	143
Blocks	4	4
Experimental design	Augmented RCBD	Augmented RCBD
Date of sowing	17 March 2025	26 September 2025
Date of transplanting	18 April 2025	3 November 2025
Research farm field	B1	B2
Spacing	90 × 45 cm	90 × 45 cm
Plants per accession plot	5	5
Labelled plants sampled per plot	3	3
Harvest considered for yield	Three successive pickings	Three successive pickings

SP, *Solanum pimpinellifolium*; SLC, *S. lycopersicum* var. *cerasiforme*; SLL, *S. lycopersicum* var. *lycopersicum*; RCBD, randomized complete block design. Checks: Sahoo, Meghdoot, TO-6242, Abhilash, US400 and Champ33. Test accessions were unreplicated within each season; checks were repeated once in each block.

Experimental design and crop management

The experiment was laid out in an augmented randomized complete block design with four blocks in each season. Each test accession was represented by a single plot, whereas each of the six checks was repeated once in every block. The replicated checks were used to estimate experimental error and to adjust for block effects (Federer and Crossa, 2012). In Summer 2025, seeds were sown on 17 March 2025 and seedlings were transplanted on 18 April 2025. In Rabi 2025–26, sowing and transplanting were undertaken on 26 September and 3 November 2025, respectively. Plants were spaced 90 cm between rows and 45 cm between plants, with

five plants per accession plot. Irrigation, weed management and plant protection were undertaken according to crop requirements. Three plants were labelled in each plot for recording fruit traits and fruit yield.

Observations recorded

Observations were recorded on ten traits: days to first flowering (DFF), fruit height (FH), fruit pH, number of locules (NOL), pericarp thickness (PT), total soluble solids (TSS), average fruit weight (AFW), fruit polar diameter (FPD), fruit equatorial diameter (FED) and fruit yield per plant (YPP). Fruits at comparable ripeness were sampled from the second and subsequent clusters for morphological and quality measurements. Fruits from the first cluster were excluded from these measurements but included in yield observations.

Days to first flowering. Recorded as the number of days from sowing to the first open flower (anthesis) in the plot.

Average fruit weight (g). Determined from 40 fruits per SP accession, 20 fruits per SLC accession and 10 fruits per SLL accession; the different sample sizes accounted for the pronounced differences in fruit size among the three groups. Average fruit weight was calculated as the total weight of sampled fruits divided by the number of fruits sampled.

Fruit height and fruit diameters (mm). Fruit height was measured on five intact ripe fruits from each labelled plant using a digital vernier caliper (resolution 0.01 mm). Fruit polar diameter was measured along the stem-to-blossom axis of longitudinally cut fruits, and fruit equatorial diameter across the widest transverse axis. Values were averaged to obtain plant and plot means.

Pericarp thickness (mm). Measured at three or four positions on each fruit half, avoiding septa and placental tissue. Readings were averaged within fruits and subsequently across sampled fruits and labelled plants.

Number of locules. Determined by counting the locules in five cut fruits from each labelled plant; both fruit halves were examined where the internal structure was irregular. Fruit counts were averaged within plants, and the three plant means were combined to obtain the plot mean.

Fruit pH. Juice was extracted from ripe fruits and filtered to remove seeds and skin. pH was measured using a digital pH meter calibrated with standard buffers of pH 4.01 and 7.01. Three readings were recorded for each pooled plant sample and averaged.

Total soluble solids (°Brix). Determined using an Atago PAL-1 digital refractometer calibrated with distilled water. Plant-level observations were averaged to obtain the plot mean.

Fruit yield per plant (kg). Recorded as the cumulative weight of fruits harvested from each labelled plant over three successive pickings, including fruits from the first cluster. The yields of the three labelled plants were averaged and expressed in kilograms per plant; yield therefore represents production during the specified harvest period.

Statistical analysis

Each season was analysed separately using the augmented design procedure implemented in the R package augmentedRCBD (Aravind et al., 2021) in R (R Core Team, 2025). The statistical model was:

$$Y_{ij} = \mu + B_j + T_i + e_{ij}$$

where Y_{ij} is the plot-level observation for entry i in block j , μ is the overall mean, B_j is the effect of block j , T_i is the effect of entry i and e_{ij} is the residual error. For each season, the degrees of freedom were 3 for blocks, 142 for entries and 15 for error, the latter being $(\text{number of blocks} - 1) \times (\text{number of checks} - 1) = (4 - 1) \times (6 - 1)$. Two analyses were performed. In the first, entries were adjusted for blocks and the entry sum of squares was partitioned into checks (5 df) and test accessions plus the test-versus-check contrast (137 df). In the second, blocks were adjusted for entries, allowing the unadjusted entry sum of squares to be partitioned into checks (5 df), test accessions (136 df) and the test-versus-check contrast (1 df) (Federer and Crossa, 2012). Season-specific means, standard errors and ranges of the test accessions were used to summarize variation, and differences between seasons were interpreted descriptively.

Genetic variability parameters

Variance components were estimated from the analysis of variance for the test accessions. Phenotypic variance (σ_p^2) was taken as the test-accession mean square, environmental variance (σ_e^2) as the residual mean square estimated from the replicated checks, and genotypic variance as $\sigma_g^2 = \sigma_p^2 - \sigma_e^2$. Genotypic and phenotypic coefficients of variation were calculated following Burton and DeVane (1953):

$$\text{GCV (\%)} = (\sqrt{\sigma_g^2} / \bar{x}) \times 100; \quad \text{PCV (\%)} = (\sqrt{\sigma_p^2} / \bar{x}) \times 100$$

where $\bar{x}$ is the mean of the test accessions. GCV and PCV were classified as low (<10%), moderate (10–20%) or high (>20%) (Sivasubramanian and Madhavamenon, 1973). Broad-sense heritability was estimated as the proportion of phenotypic variance attributable to genotypic variance (Holland et al., 2003):

$$H^2 (\%) = (\sigma_g^2 / \sigma_p^2) \times 100$$

and classified as low (<30%), moderate (30–60%) or high (>60%) (Robinson et al., 1949). Heritability estimates were interpreted for the evaluated panel under the conditions of each seasonal experiment and were not treated as evidence of additive gene action, because broad-sense heritability includes the total genotypic variance (Holland et al., 2003). Expected genetic advance (GA) at 5% selection intensity and genetic advance as per cent of mean (GAM) were calculated following Johnson et al. (1955):

$$\text{GA} = k \times (H^2/100) \times \sqrt{\sigma_p^2}; \quad \text{GAM (\%)} = (\text{GA} / \bar{x}) \times 100$$

where $k = 2.06$ is the standardized selection differential at 5% selection intensity. GAM was classified as low (<10%), moderate (10–20%) or high (>20%) (Johnson et al., 1955). Because GA and GAM were derived from

the reported PCV and heritability values, they were interpreted as comparative indices of selection potential rather than as realized responses in progenies.

RESULTS

Variation in fruit morphological traits

The 137 Varitome accessions exhibited substantial variation in fruit morphological traits in both seasons (Table 2; Figure 1). Average fruit weight ranged from 1.11 to 146.91 g in Summer and from 1.18 to 149.78 g in Rabi, with corresponding means of 26.00 ± 3.15 and 26.83 ± 3.21 g. The heaviest accession exceeded the lightest by more than 120-fold in both seasons (Figure 1), reflecting the presence of contrasting fruit-size classes within the panel. Although seasonal means were similar, the extensive within-season variation clearly differentiated small-, intermediate- and large-fruited accessions. Fruit polar diameter ranged from 3.34 to 77.61 mm in Summer and from 3.89 to 81.01 mm in Rabi, with means of 29.33 ± 1.49 and 32.01 ± 1.58 mm, respectively. Fruit equatorial diameter ranged from 9.47 to 75.57 mm and from 11.04 to 81.00 mm (means 28.23 ± 1.34 and 30.46 ± 1.41 mm), and fruit height averaged 24.63 ± 0.96 mm in Summer and 25.79 ± 0.98 mm in Rabi. All three dimensional measurements thus had numerically higher means in Rabi. Internal fruit structure also varied widely. Mean locule number was 3.02 ± 0.15 in Summer and 3.22 ± 0.17 in Rabi, with ranges of 1.81–9.97 and 1.78–11.44, respectively; these values are plot means of fruit counts rather than counts on individual fruits. Pericarp thickness ranged from 0.11 to 8.01 mm in Summer and from 0.54 to 8.00 mm in Rabi, while seasonal means were nearly identical (2.10 ± 0.12 and 2.11 ± 0.12 mm).

Table 2. Descriptive statistics for ten traits in 137 tomato Varitome accessions evaluated in Summer 2025 and Rabi 2025–26

Trait	Summer 2025		Rabi 2025–26	
	Mean $\pm$ SE	Range	Mean $\pm$ SE	Range
Days to first flowering	61.38 ± 0.52	42.92–75.21	63.36 ± 0.55	38.40–74.50
Fruit height (mm)	24.63 ± 0.96	9.39–68.33	25.79 ± 0.98	9.38–72.11
Fruit pH	4.24 ± 0.02	3.68–4.82	4.23 ± 0.02	3.66–4.80
Number of locules	3.02 ± 0.15	1.81–9.97	3.22 ± 0.17	1.78–11.44
Pericarp thickness (mm)	2.10 ± 0.12	0.11–8.01	2.11 ± 0.12	0.54–8.00
Total soluble solids ($^{\circ}$ Brix)	6.80 ± 0.10	4.70–11.28	6.85 ± 0.12	5.04–11.75
Average fruit weight (g)	26.00 ± 3.15	1.11–146.91	26.83 ± 3.21	1.18–149.78
Fruit polar diameter (mm)	29.33 ± 1.49	3.34–77.61	32.01 ± 1.58	3.89–81.01
Fruit equatorial diameter (mm)	28.23 ± 1.34	9.47–75.57	30.46 ± 1.41	11.04–81.00
Fruit yield per plant (kg)	2.06 ± 0.09	0.24–5.43	2.15 ± 0.09	0.29–5.18

SE, standard error of the mean. Values are for the 137 test accessions.

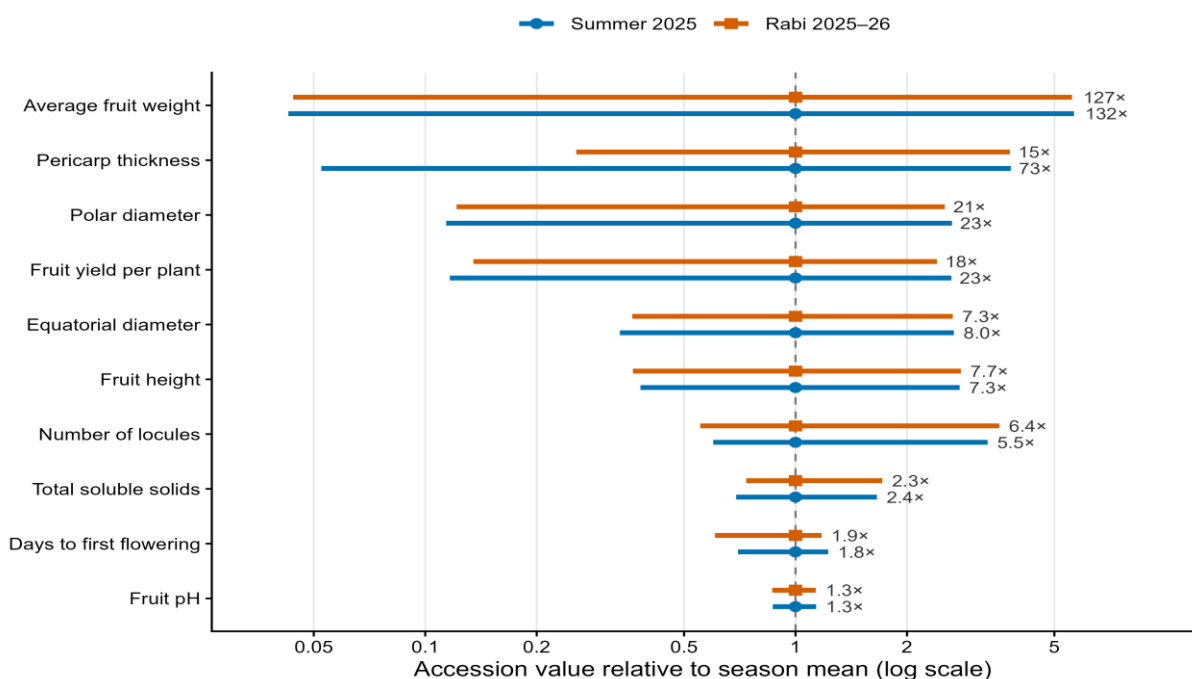


Figure 1. Spread of accession values for ten traits in the tomato Varitome panel during Summer 2025 and Rabi 2025–26. Bars span the minimum and maximum accession values expressed relative to the season mean (dashed line = 1; logarithmic scale), so traits measured in different units can be compared directly. Numbers give the maximum-to-minimum ratio. Absolute means, standard errors and ranges are given in Table 2.

Variation in flowering time, fruit quality and yield

Days to first flowering averaged 61.38 ± 0.52 in Summer and 63.36 ± 0.55 in Rabi, with ranges of 42.92–75.21 and 38.40–74.50 days, respectively (Table 2). Although mean flowering was numerically later in Rabi, the lower minimum in that season indicated that the seasonal distributions did not differ by a uniform shift across accessions. Total soluble solids varied from 4.70 to 11.28 °Brix in Summer and from 5.04 to 11.75 °Brix in Rabi, with means of 6.80 ± 0.10 and 6.85 ± 0.12 °Brix, indicating appreciable differentiation despite similar seasonal means. Fruit pH ranged from 3.68 to 4.82 in Summer and from 3.66 to 4.80 in Rabi (means 4.24 ± 0.02 and 4.23 ± 0.02); its narrow relative range contrasted with the much wider spread of fruit-size traits (Figure 1). Fruit yield per plant averaged 2.06 ± 0.09 kg in Summer and 2.15 ± 0.09 kg in Rabi, with ranges of 0.24–5.43 and 0.29–5.18 kg, respectively, representing cumulative production over three successive pickings.

Analysis of variance

The entry effect adjusted for blocks was significant for all ten traits in both seasons (Tables 3 and 4). Fruit pH was significant at $P < 0.05$ in Summer and $P < 0.01$ in Rabi, whereas all other entry effects were significant at $P < 0.01$. In the block-adjusted analysis, the test-accession component was significant ($P < 0.01$) for days to first flowering, fruit height, locule number, pericarp thickness, total soluble solids, average fruit weight, polar diameter and equatorial diameter in both seasons, and for fruit pH at $P < 0.05$ in Summer and $P < 0.01$ in Rabi. Fruit yield showed a different pattern. In Summer, the test-accession and residual mean squares were 0.69 and 0.22, respectively, and the test-accession component was significant ($P < 0.01$). In Rabi, the corresponding mean squares were 0.82 and 0.43 and the test-accession component was non-significant. Consequently, the significant overall entry effect for Rabi yield did not establish significant yield differentiation among the 137 test accessions.

The test-versus-check contrast was significant for all traits in both seasons, at $P < 0.01$ except for locule number in Rabi ($P < 0.05$). This contrast indicated differences between the average performance of the two groups but did not imply that every accession differed from the checks. Checks differed significantly for fruit height, pH, locule number and pericarp thickness in both seasons; check differences for days to first flowering, total soluble solids and fruit weight depended on the season, whereas those for polar diameter, equatorial diameter and fruit yield were non-significant in both seasons. Block effects adjusted for entries were significant for polar diameter and fruit yield in both seasons and for fruit pH in Summer. Residual mean squares increased from 23.93 to 68.09 for fruit weight and from 0.22 to 0.43 for fruit yield between Summer and Rabi, whereas that for polar diameter decreased from 57.02 to 42.85, indicating that residual variation changed in a trait-specific manner.

Table 3. Analysis of variance (augmented RCBD) for ten traits in the tomato Varitome association panel during Summer 2025

Source of variation	df	Mean squares									
		DFF	FH	pH	NOL	PT	TSS	AFW	FPD	FED	YPP
<i>Treatments adjusted for blocks</i>											
Block (ignoring entries)	3	295.46**	279.87**	0.40**	5.80**	2.83**	0.64**	5612.05**	1281.28**	835.52**	0.76*
Entries (eliminating blocks)	142	33.90**	242.38**	0.05*	2.94**	4.88**	1.60**	2097.66**	350.01**	330.29**	1.16**
Checks	5	3.50 ^{ns}	268.33**	0.17**	1.82**	2.36**	0.32*	197.74**	86.94 ^{ns}	3.92 ^{ns}	0.35 ^{ns}
Test accessions + test vs. check	137	35.01**	241.43**	0.05 ^{ns}	2.98**	4.98**	1.65**	2167.00**	359.61**	342.20**	1.19**
<i>Blocks adjusted for entries</i>											
Entries (ignoring blocks)	142	40.11**	248.16**	0.06*	3.06**	4.93**	1.62**	2215.25**	366.11**	347.82**	1.12**
Checks	5	3.50 ^{ns}	268.33**	0.17**	1.82**	2.36**	0.32*	197.74**	86.94 ^{ns}	3.92 ^{ns}	0.35 ^{ns}
Test accessions	136	40.40**	84.91**	0.05*	3.09**	0.98**	1.25**	1080.01**	279.84**	219.16**	0.69**
Test vs. check	1	183.56**	22350.08**	0.32**	4.55**	555.26**	57.60**	166694.25**	13495.27**	19565.11**	63.88**
Block (eliminating entries)	3	1.61 ^{ns}	6.10 ^{ns}	0.08*	0.28 ^{ns}	0.65 ^{ns}	0.06 ^{ns}	46.13 ^{ns}	519.23**	5.81 ^{ns}	2.77**
Residual	15	3.48	7.59	0.02	0.21	0.28	0.10	23.93	57.02	5.12	0.22

df, degrees of freedom; DFF, days to first flowering; FH, fruit height (mm); pH, fruit pH; NOL, number of locules; PT, pericarp thickness (mm); TSS, total soluble solids (°Brix); AFW, average fruit weight (g); FPD, fruit polar diameter (mm); FED, fruit equatorial diameter (mm); YPP, fruit yield per plant (kg). * and **, significant at $P < 0.05$ and $P < 0.01$, respectively; ^{ns}, non-significant.

Table 4. Analysis of variance (augmented RCBD) for ten traits in the tomato Varitome association panel during Rabi 2025–26

Source of variation	df	Mean squares									
		DFF	FH	pH	NOL	PT	TSS	AFW	FPD	FED	YPP
<i>Treatments adjusted for blocks</i>											
Block (ignoring entries)	3	282.86**	225.16**	0.32**	10.61**	2.26**	1.25**	6030.39**	1253.72**	923.25**	0.22 ^{ns}
Entries (eliminating blocks)	142	39.84**	261.31**	0.05**	3.83**	4.21**	2.02**	2110.44**	371.81**	346.79**	1.31**
Checks	5	9.09*	341.94**	0.15**	1.62**	2.46**	0.25 ^{ns}	145.55 ^{ns}	74.89 ^{ns}	12.20 ^{ns}	0.17 ^{ns}
Test accessions + test vs. check	137	40.96**	258.37**	0.05**	3.91**	4.28**	2.08**	2182.15**	382.65**	358.99**	1.35**
<i>Blocks adjusted for entries</i>											
Entries (ignoring blocks)	142	45.78**	265.93**	0.06**	4.05**	4.25**	2.04**	2236.92**	385.88**	366.03**	1.29**
Checks	5	9.09*	341.94**	0.15**	1.62**	2.46**	0.25 ^{ns}	145.55 ^{ns}	74.89 ^{ns}	12.20 ^{ns}	0.17 ^{ns}
Test accessions	136	46.55**	85.01**	0.05**	4.16**	0.96**	1.78**	1161.91**	313.23**	244.71**	0.82 ^{ns}
Test vs. check	1	124.81**	24490.40**	0.23**	1.08*	460.89**	46.05**	158895.23**	11821.22**	18635.33**	70.79**
Block (eliminating entries)	3	1.43 ^{ns}	6.63 ^{ns}	0.02 ^{ns}	0.19 ^{ns}	0.19 ^{ns}	0.33 ^{ns}	43.41 ^{ns}	587.61**	12.28 ^{ns}	1.84**
Residual	15	2.95	5.94	0.01	0.23	0.25	0.14	68.09	42.85	9.44	0.43

df, degrees of freedom; DFF, days to first flowering; FH, fruit height (mm); pH, fruit pH; NOL, number of locules; PT, pericarp thickness (mm); TSS, total soluble solids (°Brix); AFW, average fruit weight (g); FPD, fruit polar diameter (mm); FED, fruit equatorial diameter (mm); YPP, fruit yield per plant (kg). * and **, significant at $P < 0.05$ and $P < 0.01$, respectively; ^{ns}, non-significant.

Genotypic and phenotypic coefficients of variation

PCV exceeded GCV for all traits in both seasons (Table 5; Figure 2). High GCV and PCV (>20%) were recorded for average fruit weight, locule number, polar and equatorial diameters, pericarp thickness, fruit height and fruit yield per plant in both seasons; total soluble solids showed moderate values, days to first flowering low-to-moderate values and fruit pH low values. Average fruit weight exhibited the greatest relative variability, with GCV of 124.99 and 123.27% and PCV of 126.40 and 127.05% in Summer and Rabi, respectively. Locule number followed, with GCV increasing from 56.21% in Summer to 61.45% in Rabi and PCV from 58.24 to 63.25%. Equatorial diameter had GCV of 51.82 and 50.36% and PCV of 52.44 and 51.36%; the narrow GCV–PCV gap indicated a small residual contribution. In contrast, polar diameter (GCV 50.89 and 51.38%; PCV 57.03 and 55.30%) and pericarp thickness (GCV 39.91 and 39.99%; PCV 47.10 and 46.55%) showed wider gaps, indicating a larger relative environmental contribution (Figure 2). Total soluble solids showed GCV of 15.76 and 18.66% and PCV of 16.46 and 19.45%, while days to first flowering showed GCV of 9.90 and 10.42% and PCV of 10.36 and 10.77%. Fruit pH had the lowest coefficients (GCV 3.96 and 4.57%; PCV 5.30 and 5.38%); because pH is a logarithmic scale, these values do not represent proportional variation in hydrogen-ion activity or total acid content. For fruit yield, GCV declined from 33.20% in Summer to 29.01% in Rabi, whereas PCV increased from 40.19 to 42.16%, widening the PCV–GCV gap from 6.99 to 13.15 percentage points.

Table 5. Variance components, coefficients of variation, broad-sense heritability and expected genetic advance for ten traits in the tomato Varitome panel in two seasons

Trait	Season	σ^2_g	σ^2_p	GCV (%)	PCV (%)	H^2 (%)	GA	GAM (%)
Days to first flowering	Summer	36.93	40.44	9.90 (L)	10.36 (M)	91.39 (H)	11.97	19.50 (M)
	Rabi	43.59	46.57	10.42 (M)	10.77 (M)	93.66 (H)	13.17	20.78 (H)
Fruit height (mm)	Summer	77.27	84.85	35.69 (H)	37.40 (H)	91.06 (H)	17.28	70.16 (H)
	Rabi	79.07	85.05	34.48 (H)	35.76 (H)	93.01 (H)	17.67	68.52 (H)
Fruit pH	Summer	0.0282	0.0505	3.96 (L)	5.30 (L)	55.92 (M)	0.2589	6.11 (L)
	Rabi	0.0374	0.0518	4.57 (L)	5.38 (L)	72.13 (H)	0.3381	7.99 (L)
Number of locules	Summer	2.88	3.09	56.21 (H)	58.24 (H)	93.17 (H)	3.38	111.78 (H)
	Rabi	3.92	4.15	61.45 (H)	63.25 (H)	94.39 (H)	3.96	122.99 (H)
Pericarp thickness (mm)	Summer	0.7024	0.9783	39.91 (H)	47.10 (H)	71.80 (H)	1.46	69.66 (H)
	Rabi	0.7120	0.9647	39.99 (H)	46.55 (H)	73.80 (H)	1.49	70.77 (H)
Total soluble solids (°Brix)	Summer	1.15	1.25	15.76 (M)	16.46 (M)	91.71 (H)	2.11	31.10 (H)
	Rabi	1.63	1.78	18.66 (M)	19.45 (M)	92.06 (H)	2.53	36.89 (H)
Average fruit weight (g)	Summer	1056.08	1080.04	124.99 (H)	126.40 (H)	97.78 (H)	66.20	254.60 (H)
	Rabi	1093.85	1161.96	123.27 (H)	127.05 (H)	94.14 (H)	66.11	246.39 (H)
Fruit polar diameter (mm)	Summer	222.79	279.79	50.89 (H)	57.03 (H)	79.63 (H)	27.44	93.55 (H)
	Rabi	270.50	313.34	51.38 (H)	55.30 (H)	86.32 (H)	31.48	98.33 (H)
Fruit equatorial diameter (mm)	Summer	214.00	219.15	51.82 (H)	52.44 (H)	97.66 (H)	29.78	105.50 (H)
	Rabi	235.31	244.74	50.36 (H)	51.36 (H)	96.14 (H)	30.98	101.72 (H)
Fruit yield per plant (kg)	Summer	0.4677	0.6854	33.20 (H)	40.19 (H)	68.26 (H)	1.16	56.51 (H)
	Rabi	0.3890	0.8216	29.01 (H)	42.16 (H)	47.34 (M)	0.8840	41.11 (H)

Summer, Summer 2025; Rabi, Rabi 2025–26. σ^2_g , genotypic variance; σ^2_p , phenotypic variance; GCV and PCV, genotypic and phenotypic coefficients of variation; H^2 , broad-sense heritability; GA, expected genetic advance at 5% selection intensity (in trait units); GAM, genetic advance as per cent of mean. Letters in parentheses denote low (L), moderate (M) or high (H) classes: GCV, PCV and GAM, L < 10%, M 10–20%, H > 20%; H^2 , L < 30%, M 30–60%, H > 60%.

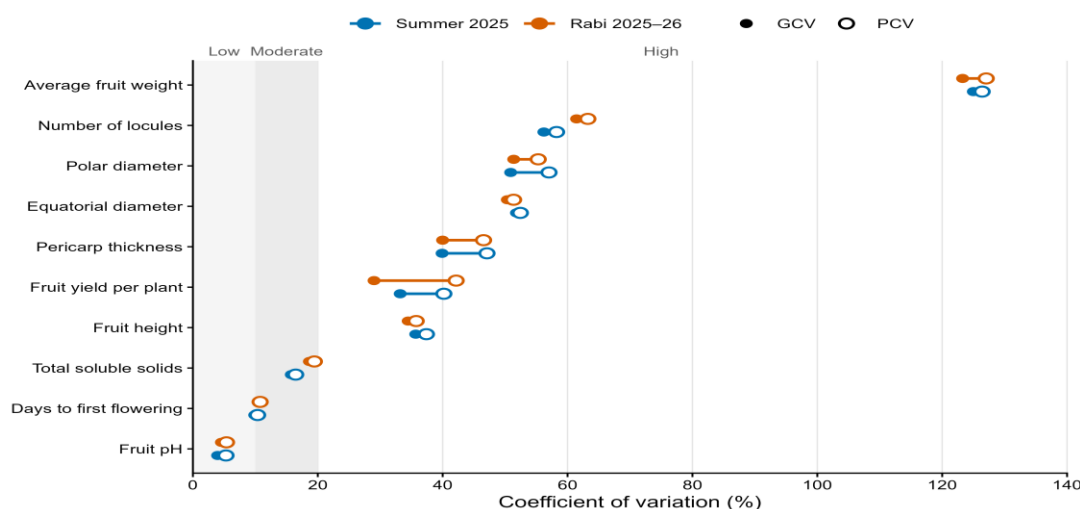


Figure 2. Genotypic (GCV, filled symbols) and phenotypic (PCV, open symbols) coefficients of variation for ten traits in the tomato Varitome panel during Summer 2025 and Rabi 2025–26. The length of each connecting line (PCV – GCV) indicates the relative environmental contribution. Shaded bands mark the low (<10%) and moderate (10–20%) classes of Sivasubramanian and Madhavamenon (1973).

Heritability and expected genetic advance

Average fruit weight, locule number, equatorial diameter, fruit height, days to first flowering and total soluble solids exhibited heritability above 90% in both seasons (Table 5; Figure 3). Heritability of fruit weight was 97.78% in Summer and 94.14% in Rabi, and corresponding estimates were 93.17 and 94.39% for locule number and 97.66 and 96.14% for equatorial diameter. Polar diameter (79.63 and 86.32%) and pericarp thickness (71.80 and 73.80%) also had high heritability. Fruit pH heritability increased from moderate (55.92%) in Summer to high (72.13%) in Rabi, whereas fruit yield heritability declined from high (68.26%) to moderate (47.34%); the Rabi yield estimate should be viewed cautiously because the corresponding test-accession component was non-significant. Genetic advance as per cent of mean was greatest for average fruit weight (254.60 and 246.39%), followed by locule number (111.78 and 122.99%), equatorial diameter (105.50 and 101.72%) and polar diameter (93.55 and 98.33%). Pericarp thickness (69.66 and 70.77%), fruit height (70.16 and 68.52%), fruit yield (56.51 and 41.11%) and total soluble solids (31.10 and 36.89%) also showed high GAM, whereas days to first flowering showed moderate-to-high GAM (19.50 and 20.78%) and fruit pH low GAM (6.11 and 7.99%). Thus, high heritability coupled with high GAM was observed for fruit height, locule number, pericarp thickness, total soluble solids, average fruit weight and both fruit diameters in both seasons, for days to first flowering in Rabi only (just above the 20% GAM limit) and for fruit yield in Summer only (Figure 3).

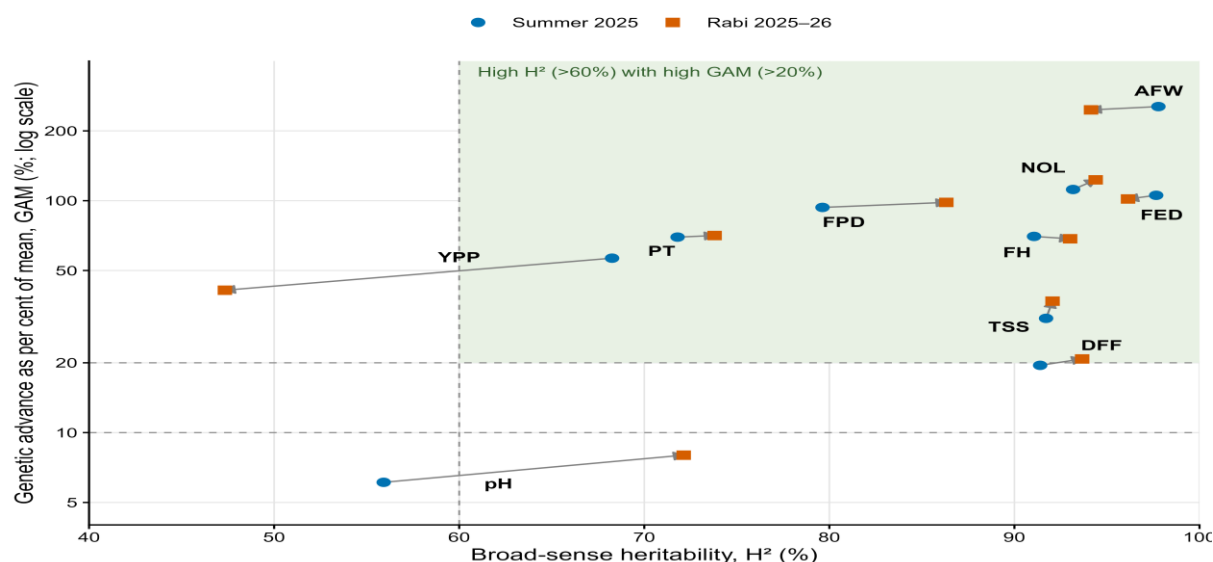


Figure 3. Broad-sense heritability (H^2) plotted against genetic advance as per cent of mean (GAM) for ten traits in Summer 2025 (circles) and Rabi 2025–26 (squares). Arrows show the seasonal shift for each trait. Dashed lines mark the class limits for H^2 (30 and 60%) and GAM (10 and 20%); the shaded area contains traits combining high H^2 with high GAM. DFF, days to first flowering; FH, fruit height; pH, fruit pH; NOL, number

of locules; PT, pericarp thickness; TSS, total soluble solids; AFW, average fruit weight; FPD, fruit polar diameter; FED, fruit equatorial diameter; YPP, fruit yield per plant.

DISCUSSION

Genetic diversity available for fruit trait improvement

The extensive variation in fruit weight, dimensions, locule number and pericarp thickness demonstrates the value of the evaluated Varitome panel as a source of contrasting fruit phenotypes. Fruit weights ranging from approximately 1 g to nearly 150 g in both seasons reflect the breadth of the material rather than variation within a single commercial fruit class. This agrees with Mata-Nicolás et al. (2020), who documented substantial morphological diversity in the original Varitome collection, and the present study extends that characterization by describing trait expression during two growing seasons at Bengaluru. The inclusion of SP, SLC and SLL accessions brings together genetic backgrounds with contrasting histories of domestication and selection. Lin et al. (2014) demonstrated that domestication and subsequent improvement involved changes in different genomic regions associated with increased fruit size, and the wide fruit-weight range observed here is consistent with the inclusion of material representing different stages of tomato diversification. Zhou et al. (2015) likewise reported morphological and molecular differentiation among cultivated tomatoes, wild relatives and introgression lines. Morphological diversity alone, however, does not identify the alleles responsible for individual traits. Selection in the present panel should therefore begin with accession-level performance within the intended fruit class, followed by evaluation of suitable parents for complementary attributes.

Selection potential for fruit weight and dimensions

Average fruit weight combined the highest GCV with high broad-sense heritability and the highest GAM in both seasons, indicating strong differentiation among accessions relative to residual variation. The small difference between GCV and PCV further supports the utility of fruit weight for preliminary phenotypic discrimination within this collection. Comparable evidence has been reported in other tomato populations: Tripodi et al. (2023) reported a fruit-weight heritability of 0.98 in a two-season heirloom evaluation, and Rasheed et al. (2023) observed substantial variability and high heritability for single fruit weight in tomato parents and hybrids. The magnitude of variability should nevertheless not be transferred directly between studies because germplasm composition and experimental designs differ.

The biological basis of fruit-weight variation can involve different developmental processes. Mu et al. (2017) showed that the derived allele of *Cell Size Regulator* (*CSR*) increased fruit weight through enlargement of pericarp cells, illustrating how cellular development can contribute to fruit-size differences in tomato germplasm; the present phenotypic analysis, however, does not establish the involvement of *CSR* or any other locus in the evaluated accessions. Equatorial diameter also showed favourable characteristics for preliminary selection, with heritability exceeding 96% and closely corresponding GCV and PCV in both seasons. Polar diameter exhibited substantial variation but a larger residual contribution, particularly in Summer, indicating that dimensional traits should be assessed individually rather than treated as interchangeable measures of fruit size.

Locule number and internal fruit structure

Locule number exhibited high variability, high heritability and high GAM in both seasons, supporting its value for distinguishing accessions with contrasting internal fruit structure. The genetic basis of locule-number variation is well established in tomato: Muñoz et al. (2011) identified two single-nucleotide polymorphisms near *WUSCHEL* associated with increased locule number, demonstrating that variation in floral meristem regulation contributes to differences in carpel and locule development. The present phenotypic results cannot, however, establish the *lc* alleles carried by individual accessions. High locule number is not inherently superior; its desirability depends on the fruit architecture required in the target market class, and locule number should be considered together with external dimensions, pericarp thickness and the intended end use.

Pericarp thickness showed high GCV and significant accession differentiation, although its heritability was lower than that of fruit weight, equatorial diameter and locule number. The wider PCV–GCV gap suggests that repeated assessment would be particularly useful when distinguishing accessions with similar thickness values. Farinon et al. (2022) evaluated a pericarp thickness index alongside other morphological traits across environments; because their index differs from the absolute thickness measured here, direct numerical comparison is inappropriate. Selection for thicker pericarp should be followed by direct assessment of firmness and postharvest behaviour, which cannot be inferred from thickness alone. Yogendra and Ramanjini Gowda (2013) demonstrated variation in firmness and shelf life in tomato progenies involving ripening mutants, underlining the need to measure these attributes directly when selecting for keeping quality.

Flowering time

Days to first flowering exhibited low-to-moderate GCV but high heritability in both seasons. This indicates that flowering differences were well resolved, although their magnitude relative to the mean was smaller than that of fruit morphological traits; consequently, GAM was only moderate to high. This pattern illustrates the quantitative genetic distinction between the reliability of phenotypic differences and their magnitude: a highly heritable trait may still offer limited proportional change when the population contains little variation relative to its mean (Johnson et al., 1955; Holland et al., 2003). Earlier flowering may be relevant to breeding for shorter crop duration, but it should not be equated with earlier marketable harvest, because fruit set, fruit development

and ripening can alter the relationship between anthesis and harvest. Selection for earliness would therefore require observations on days to first harvest and the distribution of yield over time.

Soluble solids and fruit pH

Total soluble solids combined appreciable variation with high heritability and high GAM in both seasons, and accessions exceeding 11 °Brix represent useful material for further quality evaluation. Tripodi et al. (2023) also documented soluble-solids variation among heirloom tomatoes, although they reported a lower heritability (0.58) than that observed here. This difference is not necessarily contradictory, because heritability reflects the genetic composition, environmental conditions and analytical scale of each experiment. High TSS is a useful quality attribute but does not by itself establish superior flavour: Tieman et al. (2017) demonstrated that tomato flavour involves multiple chemical components, including sugars, acids and volatile compounds. Accessions selected for high TSS should therefore be evaluated for sugar and acid composition and sensory characteristics alongside the required fruit size.

Fruit pH showed the lowest variability and a larger relative residual contribution in Summer. Because pH is logarithmic, low GCV on this scale does not establish low proportional variation in hydrogen-ion activity, and pH does not measure titratable acidity. Selection for acid-related quality should thus combine pH with titratable acidity and soluble-solids measurements. The similar seasonal means for TSS and pH indicate comparable panel averages but do not demonstrate stability of individual accessions; accession-level comparisons across seasons are needed to identify material that consistently combines desirable quality and fruit morphology.

Fruit yield and the need for replicated evaluation

Fruit yield differed from the principal fruit morphological traits in the consistency of its statistical differentiation. Although a broad range was observed in both seasons, the test-accession component was non-significant in Rabi, and the significant overall entry effect in that season reflected the checks and the test-versus-check contrast rather than differences among the 137 accessions. The larger residual mean square, wider PCV–GCV gap and reduced heritability for Rabi yield collectively indicate weaker support for selection from that trial alone. These findings do not demonstrate an absence of genetic variation; rather, accession differences were less clearly resolved against residual variation. Specific causes, such as temperature or water availability, cannot be assigned because their relationships with yield were not analysed.

Fruit weight should also be distinguished from total plant productivity. Mu et al. (2017) observed compensation between increased fruit weight and reduced fruit number in CSR material, with no corresponding increase in overall yield, and Bhandari et al. (2023) demonstrated the complexity of yield and market-specific yield components in fresh-market tomatoes evaluated over three years. Because the present yield measurement covered three successive pickings, it may capture different proportions of total production in accessions differing in growth habit or harvest duration. Further evaluation should use a defined harvest period and record fruit number, average fruit weight and marketable yield in replicated trials across environments, which would also allow estimation of genotype × environment interaction.

Interpretation of heritability and genetic advance

The high broad-sense heritability recorded for several fruit traits indicates that genotypic differences constituted a large proportion of the phenotypic variance in each season. Such estimates support preliminary discrimination among existing accessions but do not separate additive, dominance and epistatic effects; high heritability and high GAM should therefore not be presented as proof of additive inheritance or a guaranteed response to hybridization and selection (Holland et al., 2003). The conventional calculation of genetic advance assumes an approximately normal distribution, which a panel containing sharply contrasting fruit classes may not satisfy, and realized response will additionally depend on the population subjected to selection and the performance of selected progenies. GAM values are therefore most useful for comparing traits within the present analytical framework (Johnson et al., 1955). Finally, although the augmented design is appropriate for preliminary evaluation of many accessions, error is estimated only from the replicated checks; multiple plants and fruits within a plot do not supply independent field replication (Federer and Crossa, 2012).

Implications for tomato breeding

The results identify average fruit weight, equatorial diameter, locule number and total soluble solids as priority traits for preliminary accession selection, with polar diameter, fruit height and pericarp thickness providing additional information on fruit architecture. Flowering time can support phenological selection, whereas yield requires replicated confirmation, particularly given the non-significant test-accession component in Rabi. Large differences among wild, cherry-type and cultivated material are valuable for identifying contrasting donors, but they do not directly predict variation or selection response within an elite background. Promising parents should therefore be identified from accession-level records for combinations of fruit size, internal structure and quality, followed by replicated evaluation and progeny testing.

CONCLUSION

Evaluation of 137 tomato Varitome accessions during Summer 2025 and Rabi 2025–26 revealed substantial variation in fruit morphology and useful variation in soluble solids and flowering time. Average fruit weight showed the greatest relative variability, while equatorial diameter, locule number, fruit height and total soluble solids combined high variability with high broad-sense heritability and high genetic advance as per cent of mean

in both seasons, making them effective criteria for preliminary selection. Fruit yield was less clearly differentiated in Rabi and requires further replicated evaluation. The panel offers valuable material for selecting contrasting fruit types and quality attributes; multi-environment trials and progeny testing are now required to confirm accession stability and breeding value.

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