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Variability and traits association analyses in bacterial wilt resistant F_4 progenies of tomato, *Solanum lycopersicum* L. for yield and biochemical traits

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Bacterial wilt caused by *Ralstonia solanacearum* is the most devastating disease of tomato resulting in huge yield loss in commercial growing pockets of Himachal Pradesh, India. Cold tolerant strains of this pathogen evolved in the recent past, particularly pathotype IIB, are responsible for causing bacterial wilt in cold and temperate regions. High temperature and humidity favours the incidence of disease. Resistant genotypes have been developed at various research centers, located within the country and abroad but these genotypes were not found suitable for growing in Himachal Pradesh as these are lacking in one or other characteristics. Therefore, 18 bacterial wilt resistant F_4 progenies of tomato were evaluated along with two bacterial wilt resistant checks to identify the most promising progenies on the basis of nature and extent of genetic variability and heritability coupled with genetic gain. To ascertain the variability source structure, computation of principal component analysis (PCA) was also done. Estimates for phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), heritability and genetic gain were found to be high for average fruit weight, total fruits per plant, marketable fruits per plant, marketable yield per plant, gross yield per plant and lycopene content that indicates the presence of sufficient variability ensuring ample scope for improvement through selection. High heritability allied with high genetic gain suggested the presence of additive gene action and thereby these traits could be considered as reliable indices for selection**.** For PCA studies, eigenvalues were calculated for 16 morphological traits and the results revealed that the initial eight traits exhibited more than 0.5 eigenvalues and above 95 per cent of genetic variability. Hence, these traits can be considered for effective selection of developing elite bacterial wilt resistant lines in tomato.

Keywords: Genetic gain, Heritability, Lycopene, *Ralstonia solanacearum*

Tomato (*Solanum lycopersicum* L.) is one of the most popular, widely cultivated vegetable crops of special economic and medicinal importance with extensive utilization of its edible fruit. It is a rich source of vitamins (A & C), minerals[1], organic acids and antioxidant compounds (lycopene, anthocyanin and β-carotene) [2] that reciprocate anti-cancerous properties[3]. Among all the high yielding nations, India stood second with the credibility of 20.57 million tonnes annual production from an area of over 0.81 million ha[4]. It is extensively grown as an off-season vegetable crop during summer-rainy season in mid-hills of Himachal Pradesh that fetches higher prices in the markets located in the plains. Longer harvesting period and off-season production of tomato makes this crop more suitable for cultivation in mid-hill conditions. However, its cultivation is severely affected due to the devastating bacterial wilt disease caused by *Ralstonia solanacearum*[5] Smith (race 1 biovar III), prevalent in commercial growing pockets of the state[6]. This bacterium infect plants through root wounds or at sites of secondary root emergence, then colonizes the xylem vessels and spread rapidly to aerial parts of the plant through vascular system[7]. In xylem vessels, the bacterial population can multiply rapidly and reach very high levels (>1010 cells/cm of stem in tomato)[8] that elicited huge losses.

Bacterial wilt resistant tomato genotypes have been developed at various research centers, located within the country and abroad, however, they were not found suitable for growing commercially in Himachal Pradesh as these are lacking in one or other characteristics. In India, bacterial wilt incidence in tomato is approximated at 10-20% on rough basis which could reach to 90.62%[9] in certain scenarios[10].

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As far as its management is concerned, it has been proved challenging in tomato and in other crops as well with no commercial pesticide available in the market[11]. Alternatives to disease management via chemicals are limited, and host resistance is the cheapest and convenient method to control the disease[12]. Development of cultivars resistant to disease may be one of the most significant benefactions of modern plant breeding in the improvement of tomato[13]. Hence, to further enhance the production and productivity of the crop in wilt prone areas of Himachal Pradesh, identification and development of new improved disease resistant varieities/hybrids must be given due attention. The efficiency of selection depends on the nature and extent of genetic variability, degree of transmissibility of desirable characters[14] and on the actual expected genetic gain for the character in a population.

The success of any crop improvement programme through breeding strategy depends on genetically variable materials with better yield potential and resistant to pest and diseases. Hence, insight into the magnitude of variability and the extent of heritability present in the gene pool of a crop species for desirable traits is important for a plant breeder to start a judicious plant breeding programme. Here, we made an attempt to identify promising bacterial wilt resistant progenies based on nature and magnitude of genetic variability for yield and related attributes.

Materials and Methods

The investigation was carried out with 18 bacterial wilt resistant F_4 progenies of tomato *viz*., PTBWR-1 [(Palam Pride × BWR-5)-1-15], PTBWR-2 [(Palam Pride × BWR-5)-1-16], PTBWR-3 [(Palam Pride × BWR-5)-2-3], PTBWR-4 [(Palam Pride × BWR-5)-2-6], PTBWR-5 [(Hawaii 7998 × Palam Pride)-2-7], PTBWR-6 [(Hawaii 7998 × BWR-5)-3-1], PTBWR-7 [(CLN2070B-1 × 12-1)-2-8], PTBWR-8 [(CLN2070B-1 × 12-1)-2-16], PTBWR-9 [(CLN2123A-1 × BWR-5)-3-6], PTBWR-10 [Avtaar-1-3], PTBWR-11 [Avtaar-1-13], PTBWR-12 [Avtaar-1-15], PTBWR-13 [(12-1 × BWR-5)-1-7], PTBWR-14 [(12-1 × BWR-5)-2-2], PTBWR-15 [(12-1 × BWR-5)-2-13], PTBWR-16 [(12-1 × BWR-5)-2-14], PTBWR-17 [(12-1 × BWR-5)-2-18] and PTBWR-18 [(12-1 × BWR-5)-2-19]; which had been developed in the Department of Vegetable Science and Floriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur along with two bacterial wilt resistant standard checks [Palam Pink (Fig. 1A) and Palam Pride] as shown in Table 1.

To ascertain the severity of the disease, two susceptible checks, Roma and Marglobe were planted at every alternate 11th row in the experiment (Fig. 1B). These genotypes were evaluated in Randomized Complete Block Design with three replications in summer-rainy season 2016 at a spacing of 70×45 cm. Ten competitive plants from each genotype were used to record observations on the following traits *viz*., plant survival (%), days to 50 per cent flowering, days to first harvest, average fruit weight (g), fruit shape index (polar : equatorial diameter ratio), pericarp thickness (mm), locules per fruit, plant height (cm), duration of fruit harvest, total fruits per plant, marketable fruits per plant, marketable yield per plant (kg), gross yield per plant (kg), total soluble solids (°Brix), lycopene content (mg/100 g), titrable acidity (%) and ascorbic acid (mg/100 g). The following data were recorded as below:

Fig. 1 — Field view of (A) susceptible and (B) resistant checks; and (C) Bacterial ooze test of susceptible sample in laboratory

Table 1 — Visual observations recorded in bacterial wilt resistant F_4 progenies of tomato

Genotype	Determinate/ Indeterminate/ Semi-determinate	Shape of fruit	Fruit colour (RHS colour chart)	Pedicel end shape	Blossom end shape	Blossom end scar	Fruit ripening
PTBWR-1	Indeterminate	Heart	GOG172A	Deep	Pointed	Dot	Almost uniform
PTBWR-2	Semi-determinate	Obovoid	GOG166B	Medium	Flat to pointed	Linear	Almost uniform
PTBWR-3	Semi-determinate	Heart	ORG34B	Medium	Flat to pointed	Dot	Almost uniform
PTBWR-4	Semi-determinate	Heart	GOG169A	Medium	Flat	Dot	Almost uniform
PTBWR-5	Semi-determinate	Obovoid	GOG169A	Shallow	Flat to pointed	Dot	Almost uniform
PTBWR-6	Determinate	Obovoid	GOG169A	Shallow	Flat to pointed	Dot	Almost uniform
PTBWR-7	Semi-determinate	Obovoid	GOG171A	Shallow	Flat to pointed	Dot	Almost uniform
PTBWR-8	Determinate	Heart	RG44A	Medium	Flat to pointed	Dot	Almost uniform
PTBWR-9	Determinate	Obovoid	ORG35B	Medium	Flat	Dot	Almost uniform
PTBWR-10	Indeterminate	Obovoid	GOG171A	Shallow	Flat to pointed	Dot	Almost uniform
PTBWR-11	Semi-determinate	Obovoid	RG44A	Shallow	Flat	Dot	Almost uniform
PTBWR-12	Semi-determinate	Obovoid	RG42B	Medium	Flat to pointed	Dot	Almost uniform
PTBWR-13	Determinate	Slightly flattened	GOG169A	Medium	Indented	Dot	Almost uniform
PTBWR-14	Semi-determinate	Cylindrical	GOG169A	Shallow	Flat	Dot	Almost uniform
PTBWR-15	Semi-determinate	Obovoid	GOG169A	Shallow	Flat to pointed	Dot	Almost uniform
PTBWR-16	Determinate	Rectangular	GOG169A	Shallow	Indented to flat	Dot	Almost uniform
PTBWR-17	Semi-determinate	Obovoid	GOG169A	Shallow	Indented to flat	Dot	Almost uniform
PTBWR-18	Semi-determinate	Pear shaped	GOG169A	Shallow	Flat to pointed	Dot	Almost uniform
Palam Pink (Check)	Determinate	Obovoid	RG51C	Shallow	Flat	Dot	Almost uniform
Palam Pride (Check)	Indeterminate	Heart	ORG34B	Medium	Pointed	Dot	Almost uniform

Plant survival (incidence of bacterial wilt disease)

Observations on the incidence of bacterial wilt disease were recorded at weekly intervals, starting from one month after transplanting. All the plants showing wilting symptoms were subjected to bacterial ooze test (Fig. 1C) up to final count (90 days after transplanting). Plant survival (%) was calculated as:

$$\text{Plant survival (\%)} = \frac{\text{No. of healthy plants in the last recording}}{\text{No. of plants established}} \times 100$$

Determination of different traits tested

'Days to 50 per cent flowering' were recorded from transplanting date to the date when 50 per cent plants in each replication in each entry/progeny had flowered. 'Days to first harvest' were recorded from transplanting date to the date when at least one marketable fruit was harvested in 50 per cent of the plants in each replication in each entry. The 'Average fruit weight (g)' was calculated by dividing total marketable yield with total number of marketable fruits. To determine the 'fruit shape index' the ratio of polar and equatorial diameter was used[15]. The fruits of tomato progenies were grouped according to their fruit shape index as illustrated in Table 2. Polar and equatorial diameters of 5 randomly taken fruits in each entry were measured with the help of scale after cutting the fruits longitudinally and transversely and mean values were worked out. 'Pericarp thickness' was determined by recording of polar and equatorial diameter of the fruits. The pericarp thickness was measured from an equatorial section of the fruits with the help of a scale and mean value was worked out. The fruits were cut transversely to find the number of 'locules per fruit'. The 'Plant height (cm)' was measured at the final stage of harvest from ground level to the tip of main shoot, and the 'Duration of fruit harvest (days)' was recorded by deducting the number of days to first picking from the days taken to the last picking. 'Total fruits per plant' were calculated by adding the number of marketable and non-marketable fruits harvested in each picking and dividing with number of plants used for recording data, while the 'Marketable fruits per plant' were calculated by adding the number of marketable fruits harvested over all the pickings and dividing with number of plants used for recording data.

Table 2 — Grouping of tomato progenies according to their fruit shape index

Ratio (Fruit shape index)	Shape
>1.00	Oval
0.86 - 0.99	Spherical
0.71 - 0.85	Intermediate (Flat-round)
≤0.70	Flat

Marketable yield per plant (kg)

Yield is one of the most significant breeding traits of vegetable crops. For fruit-bearing vegetables like *Solanum lycopersicum* (tomato), fruit formation has a direct impact on yield. The final fruit size relies on the number as well as volume of cell layers in the fruit pericarp, which is manifested by the extent of cell division and expansion in the fertilized ovaries[16].

Hence, yield of tomato fruit is principally determined via efficiency of fruit set and the final cell count and size of the fruits. It was calculated as follows:

$$\frac{\text{Total marketable yield of all the pickings of sampled plants}}{\text{Number of plants used for recording data}}$$

Gross yield per plant (kg)

Ripe fruits were picked at an interval of 3-4 days and gross yield per plant was calculated as follows:

$$\frac{\text{Marketable yield of each picking} + \text{Non-marketable yield of each picking}}{\text{Number of plants used for recording data}}$$

Total Soluble Solids (°Brix)

A quarter part ($1/4^{th}$) of each of the five fruits chosen at random in third/fourth fruit picking was used to make a representative sample. The fruit pieces were macerated in a pestle mortar and juice was extracted. The TSS was recorded under room temperature (20°C) with the help of "Erma Hand Refractometer" by putting 2-3 drops of juice on the prism and then the reading was taken accordingly. The values recorded were expressed as per cent of juice according to the Association of Official Agricultural Chemists (A.O.A.C.) method[17].

Lycopene content (mg/100 g)

Lycopene is an acyclic carotenoid that has high nutraceutical value and confers red colour to tomato[18]. Nutritional quality of tomato is chiefly decided by its lycopene and vitamin C contents[19]. Lycopene content of ripe tomato fruits was determined by 'acetone-ether extraction method'[20]. The absorbance of the petroleum ether extract was measured in a spectrophotometer (model Spectronic-Genesys 5) at 503 nm using petroleum ether as a blank.

Lycopene (mg/100 g fruit pulp):

$$= \frac{3.1206 \text{ x absorbance} \times \text{volume made up} \times \text{dilution factor}}{1 \times \text{Weight of sample x } 1000} \times 100$$

Titrable acidity (%)

Titrable acidity was determined according to the A.O.A.C. official method 942.15[21]. Five grams of tomato juice diluted in 25 mL of distilled water and titrated by 0.1N sodium hydroxide (NaOH) to pH 8.1. The titrable acidity was expressed as gram citric acid per kilogram of tomato, according to the following equation:

$$\text{Titrable acidity} = \frac{\text{Volume of NaOH required (mL)} \times 0.1 \times 1000 \times 0.064}{\text{Mass of tomato juice sample used (g)}}$$

Here, 0.1 is the normality of NaOH (N), 0.064 is the conversion factor for citric acid

$$\text{Titrable acidity (\%)} = \text{Titrable acidity (g citric acid per kg of tomato)}/10$$

Ascorbic acid (mg/100 g)

Freshly harvested red ripe fruits were taken for the estimation of ascorbic acid by volumetric method suggested in earlier literature[22]. Oxalic acid was used as the titrating medium.

$$\text{Amount of ascorbic acid (mg/100g sample)} = \frac{0.5\text{mg} \times \text{V2mL} \times 100\text{mL}}{\text{V1mL} \times 10\text{mL} \times \text{weight of the sample}} \times 100$$

Statistical analysis

Average values for each genotype in each replication for the traits studied except plant survival were used for statistical analysis. The analyses of variance were computed as per the standard method given by Sukhatme and Panse[23]. Coefficients of variation (both PCV and GCV), heritability and genetic gain were also calculated as per standard techniques[24, 25]. The statistical analysis was carried out by using OPSTAT software. Recorded data for all the studied traits were subjected to Principal Component (PC) Analysis using SPSS-19 statistical software. The PC was used to determine the extent of genetic variation among the genotypes. Eigen values were obtained from PC, which were used to determine the relative discriminative power of the axes and their associated characters.

Results and Discussion

Genetic variability, Heritability and Genetic gain

Analysis of variance revealed significant differences among progenies for all the traits except plant survival as shown in Table 3. Analysis of

Table 3 — Analysis of variance for different traits in F_4 progenies of tomato

Characters	Mean squares		
	Replication	Treatment	Error
Df	2	19	38
Plant survival (%)	2.409	11.414	2.767
Days to 50 per cent flowering	222.517	51.049*	8.341
Days to first harvest	147.467	25.860*	5.765
Average fruit weight (g)	30.752	442.196*	19.140
Fruit shape index	0.007	0.028*	0.004
Pericarp thickness (mm)	0.577	1.344*	0.269
Locules per fruit	0.001	1.759*	0.224
Plant height (cm)	64.894	1,063.239*	74.569
Duration of fruit harvest (days)	23.267	54.150*	10.863
Total fruits per plant	.655	91.375*	3.196
Marketable fruits per plant	1.292	48.934*	2.155
Marketable yield per plant (kg)	0.018	0.057*	0.007
Gross yield per plant (kg)	0.059	0.091*	0.008
Total soluble solids (°Brix)	0.006	0.291*	0.125
Lycopene content (mg/100g)	0.085	6.064*	0.082
Titrable acidity (%)	0.006	0.020*	0.005
Ascorbic acid (mg/100g)	1.442	11.853*	1.429

[*Significant at 5% level of significance]

variance revealed non-significant differences for plant survival as all the progenies and standard checks showed high degree of resistance to bacterial wilt disease (plant survival >85%). The nature and degree of genetic variability in a crop is of paramount importance in selecting the best genotypes for making rapid improvement in yield and related characters as well as to select the most potential parents for making the hybridization programme successful. The knowledge of phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) is helpful in predicting the amount of variation present in the given genetic stock which in turn helps in formulating an efficient breeding programme. The estimates of PCV and GCV were worked out for all the characters included in the present study except plant survival (%). The data presented in Table 4 show PCV at higher magnitude than their corresponding GCV for all the characters studied as observed earlier by Khuntia *et al*[26]. The phenotypic coefficient of variation ranged from 4.88 to 48.48%. High PCV was reported for lycopene content (48.48%), marketable fruits per plant (35.71%), total fruits per plant (35.02%), locules per fruit (27.87%), marketable yield per plant (26.97%), gross yield per plant (26.84%), plant height (25.96%), average fruit weight (24.69%) and titrable acidity (23.46%). High values of PCV are indicative of sufficient variability ensuring ample scope for improvement through selection. Moderate PCV was exhibited for pericarp thickness (15.30%), days to 50 per cent flowering (14.86%), ascorbic acid (14.50%), fruit shape index (11.61%), duration of fruit harvest (10.79%) and TSS (10.27%), while days to first harvest (4.88%) had low PCV.

The phenotypic coefficient of variation alone does not reveal the relative amount of variation, hence the different aspects of genetic parameters were worked out. In the experimental material, wide range of genotypic variability was observed for the characters under study ranging from 3.58 to 47.52%. High GCV was observed in case of lycopene content (47.52%), marketable fruits per plant (33.47%), total fruits per plant (33.26%), gross yield per plant (23.55%), plant height (23.44%), locules per fruit (23.24%), average fruit weight (23.17%) and marketable yield per plant (22.70%). However, moderate GCV was exhibited by titrable acidity (16.35%), ascorbic acid (12.21%), days to 50 per cent flowering (11.80%) and pericarp thickness (11.57%). Low estimates of GCV were observed for fruit shape index (9.45%), duration of fruit harvest (8.15%), TSS (5.69%) and days to first harvest (3.58%). The results are in agreement with the earlier findings of various researchers for lycopene content, total fruits per plant, average fruit weight, locules per fruit, plant height, marketable yield per plant and marketable fruits per plant for both PCV and GCV[26]. High PCV estimate was also reported for titrable acidity[26]. Low PCV and GCV estimates for days to first harvest were also illustrated in previous study[27]. In contrary, low estimates of PCV and GCV were found for duration of fruit harvest[27]. Low estimates of GCV were also reported for TSS in previous researches[26,27].

Table 4 — Estimates of PCV, GCV, heritability and genetic gain for fruit yield and other traits in F_4 progenies of tomato

Traits	PCV (%)	GCV (%)	h^2_{bs} (%)	GA as percentage of mean
Days to 50 per cent flowering	14.86 (M)	11.80 (M)	63.06 (H)	19. (M)
Days to first harvest	4.88 (L)	3.58 (L)	53.74 (M)	5.40 (L)
Average fruit weight (g)	24.69 (H)	23.17 (H)	88.05 (H)	44.79 (H)
Fruit shape index	11.61 (M)	9.45 (L)	66.36 (H)	15.86 (M)
Pericarp thickness (mm)	15.30 (M)	11.57 (M)	57.16 (M)	18.02 (M)
Locules per fruit	27.87 (H)	23.24 (H)	69.53 (H)	39.92 (H)
Plant height (cm)	25.96 (H)	23.44 (H)	81.55 (H)	43.61 (H)
Duration of fruit harvest (days)	10.79 (M)	8.15 (L)	57.05 (M)	12.68 (M)
Total fruits per plant	35.02 (H)	33.26 (H)	90.19 (H)	65.07 (H)
Marketable fruits per plant	35.71 (H)	33.47 (H)	87.86 (H)	64.63 (H)
Marketable yield per plant (kg)	26.97 (H)	22.70 (H)	70.81 (H)	39.35 (H)
Gross yield per plant (kg)	26.84 (H)	23.55 (H)	77.04 (H)	42.59 (H)
Total soluble solids (°Brix)	10.27 (M)	5.69 (L)	30.73 (M)	6.50 (L)
Lycopene content (mg/100g)	48.48 (H)	47.52 (H)	96.06 (H)	95.94 (H)
Titrable acidity (%)	23.46 (H)	16.35 (M)	48.54 (M)	23.46 (M)
Ascorbic acid (mg/100g)	14.50 (M)	12.21 (M)	70.86 (H)	21.17 (M)

[PCV, Phenotypic coefficient of variation {Low (L): <10%, Moderate (M): 10-20%, High (H): >20%}; GCV, Genotypic coefficient of variation {Low (L): <10%, Moderate (M): 10-20%, High (H): >20%}; h^2_{bs}, Heritability (broad sense) {Low (L): <30%, Moderate (M): 30-60%, High (H): >60%}; and GA, Genetic gain {Low (L): <10%, Moderate (M): 10-30%, High (H): >30%}]

The estimates of heritability are of considerable practical importance to the breeders as these help in the formation of an efficient and pragmatic programme. Heritability (broad sense) estimates are more informative as they indicate relative importance of genotypic and environmental contribution to the variability exhibited and the reliance that can be placed on phenotypic value during selection. In the present study, high to moderate heritability estimates were obtained for most of the characters. The estimate of heritability for different characters presented in Table 4 ranged from 30.73 (TSS) to 96.06% (lycopene content). Apart from lycopene content, the other characters which recorded high heritability were total fruits per plant (90.19%), average fruit weight (88.05%), marketable fruits per plant (87.86%), gross yield per plant (77.04%), ascorbic acid (70.86%), marketable yield per plant (70.81%), locules per fruit (69.53%), fruit shape index (66.36%) and days to 50 per cent flowering (63.06%). However, pericarp thickness (57.16%), duration of fruit harvest (57.05%), days to first harvest (53.74%), titrable acidity (48.54%) and TSS (30.73%) exhibited moderate heritability.

Selection for a particular character is generally made on the basis of its phenotypic expression which is the result of both genotype and environment. Accordingly, the phenotypic superiority of plants over the original population is not solely due to favourable environmental factors. In such a situation, genetic gain gives good idea for actual gain to be made in the population under evaluation. High heritability does not necessarily mean high genetic gain and is insufficient alone to make improvement through simple phenotypic selection. The heritability estimates are more beneficial when used to estimate genetic gain and hence, the genetic gain provides an edge over heritability as a guiding factor to breeders in various selection programmes. In the present study, high genetic gain was observed for lycopene content (95.94%), total fruits per plant (65.07%), marketable fruits per plant (64.63%), average fruit weight (44.79%), plant height (43.61%), gross yield per plant (42.59%), locules per fruit (39.92%) and marketable yield per plant (39.35%). High estimates of genetic gain for these characters suggested that these characters were governed by additive gene effects and selection will be rewarding for improvement of these characters. Moderate genetic gain was observed for titrable acidity (23.46%), ascorbic acid (21.17%), days to 50 per cent flowering (19%), pericarp thickness (18.02%), fruit shape index (15.86%) and duration of fruit harvest (12.68%). Low genetic gain was observed for TSS (6.50%) and days to first harvest (5.40%). Both heritability and genetic advance estimates were also recorded high for average fruit weight, plant height, total fruits per plant, locules per fruit, lycopene content, marketable fruits per plant, marketable yield per plant and gross yield per plant in earlier findings by various researchers[26,27]. High heritability estimate was also observed for days to 50 per cent flowering[26]. Low genetic gain was also recorded in case of days to first harvest[27] and TSS[26,27].

Principal component analysis

Genetic variability is the main key to develop improved varieties for a crop. Thus, genetic evaluation of a particular variety for various characters is an important part of vegetable breeding. But the fact is that the whole process of evaluation for a large number of characters is very incommodious and time-taking. For such instances, principal component analysis (PCA) may be used to lessen the prolixity of the data set. It is a statistical tool which facilitates the formation of small number of uncorrelated principal components from a large number of correlated variables. PCA of phenotypic data is usually carried out to describe morphological variation among the genotypes and to estimate population structure[28]. In the present investigation, eigenvalues were calculated for 16 morphological characters of tomato based on principal component analysis as shown in Table 5. Out of these 16 morphological traits, initial eight traits presented more than 0.5 eigenvalues and unveiled more than 95 per cent of genetic variability present among 20 tomato genotypes. The maximum variation of 18.78% was explained by first latent vector followed by 16.34% (second vector) and 13.30% (third vector). PC1 (days to 50 per cent flowering) has highest eigenvalue (4.927) and accounts for (30.793%) of genetic variability. The other seven PCs have eigenvalues in decreasing order *i.e.*, PC2 (2.827), PC3 (2.052), PC4 (1.791), PC5 (1.104), PC6 (1.014), PC7 (0.929) and PC8 (0.580) and exhibited 17.667%, 12.825%, 11.195%, 6.903%, 6.340%, 5.804% and 3.627% of genetic variability respectively.

The quantitative traits that contributed more positively to PC1 were marketable fruits per plant, total fruits per plant and gross yield per plant which are positively related with yield while average fruit weight and TSS observed to have negative effect on yield and it was cleared from the values of PC1 which is also presented in Table 6. Principal component 2 (PC2) had 17.667% of the total variability. Characters like fruit shape index and days to 50 per cent flowering were observed in PC2 which are positively correlated with yield while locules per fruit had negative correlation with yield whereas traits like lycopene content; pericarp thickness; ascorbic acid, and plant height were explained by PC3, PC4, PC5 and PC6, respectively as shown in Table 6. Traits like titrable acidity, days to first harvest and duration of fruit harvest were explained by PC6, PC7 and PC8, respectively but all are negatively correlated with yield. Hence, selection towards negative direction should be made for titrable acidity, days to first harvest and duration of fruit harvest.

Even though correlation analysis facilitates in yielding the effective characters in order of indirect selection of superior genotypes but contrarily, principal component analysis is an appropriate multivariate technique in distinguishing the independent principal components that are effective on plant traits individually. Hence, PCA also helps breeders for genetic improvement of characters such as yield that have low heritability specifically in early generations via indirect selection for traits effective on yield[29]. Principal component analysis is a technique which identifies plant traits contributed most to the observed variation within a group of genotypes and it had a practical application in the selection of parental lines for breeding purpose.

Table 5 — Principal components based on eigenvalues of 16 traits of tomato

PC	Trait	Eigen value	% of Variance	Cumulative %
PC1	Days to 50 per cent flowering	4.927	30.793	30.793
PC 2	Days to first harvest	2.827	17.667	48.460
PC 3	Average fruit weight (g)	2.052	12.825	61.285
PC 4	Fruit shape index	1.791	11.195	72.480
PC 5	Pericarp thickness (mm)	1.104	6.903	79.383
PC 6	Locules per fruit	1.014	6.340	85.723
PC 7	Plant height (cm)	0.929	5.804	91.527
PC 8	Duration of fruit harvest (days)	0.580	3.627	95.154
PC 9	Total fruits per plant	0.8	1.987	97.141
PC 10	Marketable fruits per plant	0.221	1.381	98.522
PC 11	Gross yield per plant (kg)	0.121	0.757	99.279
PC 12	Total soluble solids (°Brix)	0.059	0.369	99.648
PC 13	Lycopene content (mg/100 g)	0.036	0.223	99.871
PC 14	Titrable acidity (%)	0.014	0.085	99.957
PC 15	Ascorbic acid (mg/100 g)	0.005	0.032	99.989
PC 16	Marketable yield per plant (kg)	0.002	0.011	100.000

Principal component scree plot

Similar illustration can also be drawn from scree plot (Fig. 2) that demonstrates the percentage of variance connate with each principal component attained by depicting a graph between eigenvalues and principal components as a result of which it helps in determining the appropriate number of principal components; through this we get an 'elbow' in the scree plot. The component number is considered to be the point at which the remaining eigenvalues are relatively small (<1) and all are of the same size. The scree plot displayed eight principal components and

Table 6 — Component matrix for various principal components

Trait	Components							
	1	2	3	4	5	6	7	8
Days to 50 per cent flowering	–0.491	0.764	–0.066	0.266	0.089	–0.036	–0.106	0.053
Days to first harvest	–0.489	–0.203	–0.269	0.393	–0.221	0.195	–0.513	0.6
Average fruit weight	–0.640	0.099	–0.563	0.227	0.341	0.017	0.210	–0.124
Fruit shape index	–0.034	0.797	–0.329	–0.304	–0.116	–0.221	0.164	0.132
Pericarp thickness	0.457	0.375	–0.047	0.623	–0.343	–0.022	–0.279	–0.059
Locules per fruit	–0.433	–0.724	0.008	0.032	0.225	0.255	–0.007	0.122
Plant height	–0.341	0.540	0.209	0.230	–0.2	0.429	0.373	0.217
Duration of fruit harvest	0.398	0.550	0.283	–0.330	–0.034	0.389	–0.252	–0.336
Total fruits per plant	0.953	–0.198	0.082	0.073	–0.016	0.017	–0.004	0.039
Marketable fruits per plant	0.972	–0.157	0.040	0.050	–0.060	–0.016	–0.079	0.078
Gross yield per plant	0.759	0.063	–0.338	0.427	0.202	0.132	0.206	0.006
Total soluble solids	–0.560	–0.084	0.380	0.557	0.101	0.119	–0.012	–0.411
Lycopene content	–0.014	–0.219	0.671	0.350	–0.325	–0.174	0.425	0.077
Titrable acidity	–0.034	0.284	0.488	0.274	0.432	–0.568	–0.213	0.106
Ascorbic acid	0.277	0.306	0.529	–0.077	0.540	0.371	–0.050	0.269
Marketable yield per plant	0.737	0.021	–0.434	0.408	0.240	0.045	0.162	–0.032

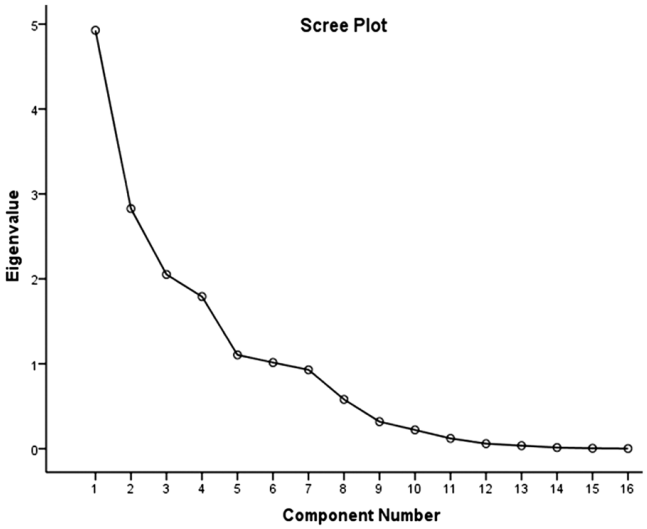

Fig. 2 — Scree plot illustrating eigenvalues for various principal components

showed that the eigenvalues are decreasing from PC1 to PC8 which are the most important components of variation (Fig. 2).

This study shows that high to moderate values of PCV and GCV are indicative of sufficient variability ensuring ample scope for improvement through selection, whereas the traits with low PCV and GCV indicated less scope of improvement. High heritability in broad sense suggested that large portion of phenotypic variance was accountable to the genotypic variance. The traits with high heritability estimates were less influenced by the environment and selection based on phenotypic performance would be reliable. Traits with low heritability indicate that they are influenced by the environment and selection can be deferred at later stages. High to moderate heritability with high to moderate genetic gain indicated preponderance of additive gene action which suggested that the traits can be improved through simple selection. The traits with moderate heritability and low genetic gain suggested preponderance of non-additive gene action and consequently improvement of these traits is possible through recombinant breeding.

In case of PCA analysis, the cumulative variance of 95.154% by the first eight principal components with eigenvalues of more than 0.5 indicated that the identified characters within these axes displayed immense influence on the phenotype of the cultivars and could effectively be used for selection. The above results suggest that the traits *viz.*, marketable fruits per plant, total fruits per plant, gross yield per plant, average fruit weight, total soluble solids (TSS), fruit shape index, days to 50 per cent flowering, locules per fruit, lycopene content, pericarp thickness, ascorbic acid, plant height, titrable acidity, days to first harvest and duration of fruit harvest are important for improving yield and quality traits. These traits can be considered for effective selection of parents for hybridization program for broadening the genetic base in the population as well as to develop elite lines or F_1 hybrids. Moreover, selection of the genotypes with the highest marketable yield per plant and its components should be suggested as one of the best breeding strategies for genetic improvement of tomato. Highest variation in PC1 accounts for 30% of the available variability, therefore the selection of genotypes based on PC1 will be maximum rewarding. After PC8, remaining eight components correspond to only 5% of variability; as a result these traits can be avoided for further analysis. The similar results have been emphasized by many researchers in previous studies[30].

Conclusion

For most of the parameters, high to moderate estimates of PCV and GCV along with high heritability and genetic gain were observed. Both PCV and GCV estimates were found to be high for average fruit weight (24.69%, 23.17%), total fruits per plant (35.02%, 33.26%), marketable fruits per plant (35.71%, 33.47%), marketable yield per plant (26.97%, 22.70%), gross yield per plant (26.84%, 23.55%) and lycopene content (48.48%, 47.52%), which indicate the presence of sufficient variability ensuring ample scope for improvement through selection. High heritability allied with high genetic gain was observed for average fruit weight (88.05%, 44.79%), marketable fruits per plant (87.86%, 64.63%), marketable yield per plant (70.81%, 39.35%), gross yield per plant (77.04%, 42.59%) and lycopene content (96.06%, 95.94%) which suggested the presence of additive gene action and thereby these traits could be considered as reliable indices for selection**.** Whereas, recombination breeding will prove effective for the characters *viz.*, days to first harvest, duration of fruit harvest and TSS as these traits exhibited moderate to low estimates of PCV, GCV, h^2_{bs} and GA. According to PCA analysis, eigenvalues are decreasing from PC1 to PC8 which are the most important components of variation. Highest variation in PC1 accounts for 30% of the available variability, therefore the selection of genotypes based on PC1 will be maximum rewarding.

Conflict of Interest

Authors declare no competing interests.

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