J. Bangladesh Acad. Sci. 49(2); 255-269: December 2025 DOI:https://doi.org/10.3329/jbas.v49i2.86721

Journal of Bangladesh Academy of Sciences

Journal homepage: http://www.bas.org.bd/publications/jbas.html

Research Article

Genetic variability and trait associations pertaining to agronomic, post-harvest, and nutritional characteristics of the parents and hybrids of tomato (*Solanum lycopersicum* L)

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ARTICLE INFO

Article History

Received: 24 August 2025
Revised: 18 September 2025
Accepted: 19 September 2025

Keywords: Tomato fruit qualities, Agronomic performance, Genetic variability, Trait relationship.

ABSTRACT

In the current study, ten F_1 hybrids and their five parents were evaluated for agronomic, post-harvest, and nutritional traits. Significant genetic variation was observed among the traits, which grouped the planting materials into four phylogenetic clades. High heritability, coupled with high genetic advance was recorded for fruits per plant (99.61% and 170.55%), single fruit weight (99.06% and 102.09%), and vitamin C content (99.98% and 177.53%), suggesting that these traits are governed predominantly by additive gene action. Pearson's correlation and path coefficient analyses identified fruit diameter, number of secondary branches, single-fruit weight, and skin thickness as key traits positively associated with fruit yield, while increased skin thickness also contributed to enhanced shelf-life. Based on mean performance, the hybrids BT-15 × BT-3, BT-8 × BT-15, and BT-8 × BT-14 emerged as promising candidates for high yield. In addition, BT-8 × BT-11 and BT-8 × BT-15 exhibited superior shelf life and nutritional quality. Overall, the findings highlight the potential of integrating yield, post-harvest, and nutritional traits into selection indices for the development of superior tomato hybrids.

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops worldwide, valued for its economic significance and rich nutritional composition. It is an important source of vitamin C, provitamin A, lycopene, and essential minerals, which contribute to dietary health and help prevent chronic diseases (Gonzalez-Vega et al., 2021). Beyond its nutritional profile, farmers prefer tomato cultivation for its relatively short life cycle, higher yields, and broad adaptability to varying agro-climatic conditions (Lin et al., 2014). Despite its broad adaptability and short life cycle, Bangladesh faces a substantial yield gap in tomato production, averaging 14.05 t/ha compared with the global mean of 33 t/ha (FAOSTAT, 2023). This gap underscores the need for breeding early-maturing, high-yielding tomato hybrids that also possess superior post-harvest and nutritional qualities to meet the growing demand from both producers and consumers.

Moreover, tomato is a fleshy vegetable, particularly vulnerable to post-harvest deterioration due to poor shelf life, skin thickness, storability, and resistance to mechanical damage, which are essential for preserving quality during transport and storage (Sinha et al., 2019). However, many existing commercial hybrids in Bangladesh fail to combine these attributes, often exhibiting either late maturity, poor shelf life, or suboptimal yield (Islam et al., 2021). To overcome these constraints, tomato-

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breeding strategies must integrate multiple trait targets, including earliness, productivity, storability, and nutritional quality, thereby minimizing reliance on tomato imports.

Effective tomato improvement relies on the analysis of genetic variability and trait interrelationships, which provide the basis for informed selection of superior genotypes (Johnson et al., 1955). Correlation analysis helps identify the degree and direction of associations among traits, facilitating indirect selection for complex targets such as yield and quality (Dewey and Lu, 1959). While previous studies have often evaluated agronomic, post-harvest, or nutritional traits individually, integrated assessments of these traits in early-maturing, high-yielding hybrids are limited. The present study evaluates diverse early-maturing tomato hybrids for agronomic performance, post-harvest quality, and nutritional composition, alongside assessments of genetic variability and trait associations. By integrating these dimensions, the study provides a robust framework for selecting superior hybrids that combine productivity, early maturity, post-harvest performance, and nutritional enhancement, contributing to sustainable tomato breeding and improved food security in Bangladesh.

Materials and Methods

Ten hybrids with five parents and a check variety were evaluated for quantitative, post-harvest, and nutritional traits in the research field of Sher-e-Bangla Agricultural University during the 2018-19 rabi season. A Randomized Complete Block Design (RCBD) with three replications was used, with row-to-row spacing of 60 cm, and plant-to-plant spacing of 40 cm. All intercultural operations and fertilizer doses were carried out according to the BARI handbook (2017). The complete list of sixteen planting materials employed in this study is presented in Table 1. The planting materials were assessed by recording various agronomic parameters, including days to 50% flowering, plant height (cm), number of secondary branches, number of fruits per cluster, number of fruits per plant, single fruit weight (g), fruit diameter (mm), fruit length (mm), days to first harvesting, and yield per plant (kg); and post-harvest parameters viz., number of locules per fruit, shelf life, skin thickness, and nutritional qualities including vitamin C content, brix percentage (%), titrable acidity (%). Data collection was performed from thirty random plants per planting material. Considering these data, Statistix 10 was used to perform the analysis of variance and the least significant difference (LSD) test. Additionally, the genetic variability components, correlation coefficient, and clustering analysis using the Euclidean complete method were performed with the aid of R software (version 4.3.1), whereas the clustering dendrogram was constructed using ggrplot2. Moreover, the remaining visual presentations were prepared using Origin (2023b) software.

The brix percentages or total soluble solid content were evaluated by using a portable refractometer (ERMA, Tokyo, Japan), whilst an oxidation-reduction titration procedure suggested by Tee et al. (1988) was followed to assess the vitamin C contents.

Vitamin-C =

$$\frac{0.5 \text{ dye required for tomato juice} \times 100 \times 100}{\text{dye required for L – ascorbic acid x 5 weight for fruit}}$$

and according to Panse and Sukhatme (1967), titrable acidity was assessed following the formula below:

Titrable acidity (%) =

$$\frac{\text{titrate} \times \text{normality of alkali} \times \text{volume made up} \times \text{equivalent wt. of acid} \times 100}{\text{volume of sample} \times \text{weight of sample} \times 100}$$

Table 1. List of planting materials used for the experiment.

Sl. no.	Designation	Name
Parents		
1.	BT-8	BARI Tomato-8
2.	BT-15	BARI Tomato-15
3.	BT-14	BARI Tomato-14
4.	BT-11	BARI Tomato-11
5.	BT-3	BARI Tomato-3
F_1 cross combinations		
6.	BT-8 × BT-15	BARI Tomato-8 × BARI Tomato-15
7.	BT-8 × BT-14	BARI Tomato-8 × BARI Tomato-14
8.	BT-8 × BT-11	BARI Tomato-8 × BARI Tomato-11
9.	BT-8 × BT-3	BARI Tomato-8 × BARI Tomato-3
10.	BT-15 × BT-14	BARI Tomato-15 × BARI Tomato-14
11.	BT-15 × BT-11	BARI Tomato-15 × BARI Tomato-11
12.	BT-15 × BT-3	BARI Tomato-15 × BARI Tomato-3
13.	BT-14 × BT-11	BARI Tomato-14 × BARI Tomato-11
14.	BT-14 × BT-3	BARI Tomato-14 × BARI Tomato-3
15.	BT-11 × BT-3	BARI Tomato-11 × BARI Tomato-3
16.	BHT-4 (Check variety)	BARI Hybrid Tomato-4

Note: BARI: Bangladesh Agricultural Research Institute

Results and Discussion

Mean performance of hybrids and their parents

In a breeding program, the breeders' primary objective is to identify genetic variations among the traits of interest, thereby accumulating favorable genes into new cultivars. In the current study, we observed significant genetic differences between F_1 hybrids and their parents, suggesting ample opportunities for varietal development (Table 2). The mean performance for yield-contributing traits and post-harvest traits was presented in Table 3. Among the hybrids, the highest fruit yield performance was found in BT-15 × BT-3 followed by BT-8 × BT-15 and BT-8 × BT-14, surpassing the better parent BT-3. Furthermore, for single fruit weight per plant, the hybrids BT-15 × BT-14 produced the highest fruit weight, possibly due to the accumulation of genes from the parental line, as BT-15 yielded the highest individual fruit weight among the parents. Variations in fruit yield performance among tomato cultivars were also reported by Meena et al. (2017) and Kumar et al.

Table 2. Analysis of variances (MS values) of eighteen quantitative, post-harvest and nutritional traits of tomato.

Sources	df	D50%F	PH	NSB	NFC	NFP	SFW	FD	FL	DFH	YPP	NL	ST	SL	VC	BRIX	TA
Replications	2	2.69	2.83	0.01	0.13	2.34	2.28	11.89	7.35	1.58	0.01	1.90	0.07	14.65	16.46	0.15	0.01
Geno types	15	19.42**	381.83*	8.06**	10.86**	8968.69**	3181.72**	589.35**	355.24**	202.92	1.02**	3.51**	4.53**	137.71**	5161.06*	1.54*	0.03**
Error	30	1.29	4.75	0.02	0.14	12.62	10.53	8.40	4.08	6.58	0.02	0.65	0.03	2.20	16.56	0.02	0.01

Note: D50%F=Days of 50% flowering; PH=Plant height (cm); NSB=Number of secondary branches, NFC= Number of fruits per cluster; NFP= Number of fruits per plant; SFW=Single fruit weight (g); FD=Fruit diameter (mm); FL=Fruit length (mm); DFH=Days of first harvesting; YPP= Yield per plant (kg), NL = Number of locules per fruit, ST = Skin thickness (mm), SL = Shelf-life duration (Days after harvesting), VC = Vitamin C (mg/100g), Brix content and TA = Titrable acidity (%).

(2020). It is found that the number of fruits per cluster and per plant is a reliable indicator of the yield potential of tomato hybrids. In this experiment, the F_1 hybrids BT-8 × BT-11 and BT-15 × BT-11 demonstrated the highest number at both pre- and post-flowering, while the parent BT-11exhibited the maximum number of fruits per cluster and fruit per plant, indicating the additive gene action in controlling the inheritance of these traits, which suggested that an early selection from these combinations would be advantageous. Furthermore, the superior short stature and early maturity were observed in the hybrids BT-8 × BT-11 and BT-15 × BT-11 compared with the parent BT-15, the earliest-maturing genotype among the parental lines. Therefore, selecting these promising hybrids would be advantageous and would expand the scope for isolating potential early-maturing, high-yielding recombinant lines in the future.

In the current study, the post-harvest and nutritional qualities of the hybrids, parents, and check variety were also assessed (Fig. 1). For tomato cultivars, thicker flesh for prolonged preservation is a prerequisite. The hybrid BT-8 × BT-15, followed by BT-8 × BT-11, which showed the highest shelf-life, and skin thickness, had higher values than the corresponding better parent in the cross combinations. Hosen et al. (2022) and Rasheed et al. (2022) are consistent with the experimental findings. In terms of nutritional quality, the hybrid BT-8 × BT-11 showed higher values for vitamin C and Brix percentage than the parental lines used in the crosses. Additionally, the highest titrable acidity was found in hybrid BT-11 × BT-3. Kumar (2021) and Farwah et al. (2023) reported that vitamin C and Brix percentages were within the ranges observed in tomato accessions. Therefore, these findings suggest that the selected hybrids could serve as preferred genetic resources for developing improved tomato hybrids.

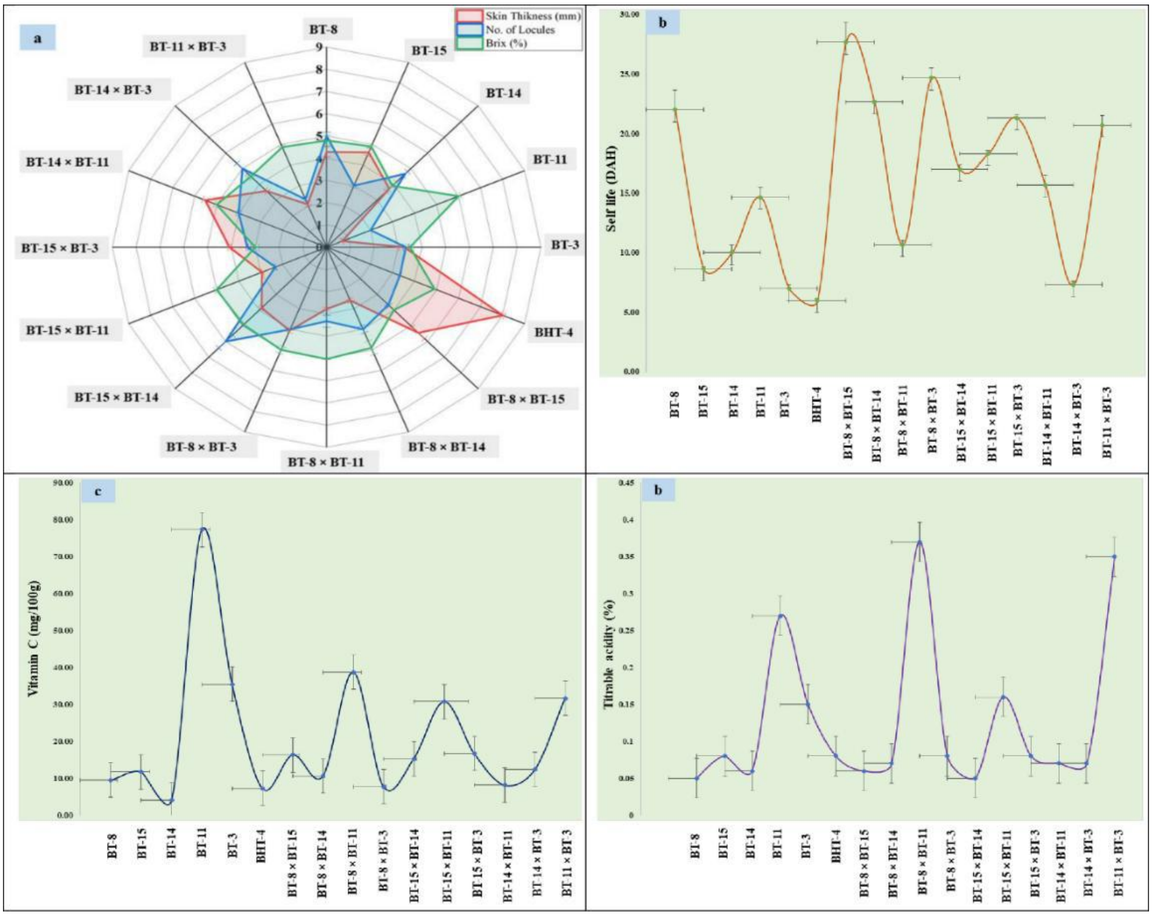

Fig. 1.Mean performance of ten hybrids, five parents and check variety for (a) skin thickness (mm), number of locules per fruit and brix content; (b) shelf-life duration (days after harvesting); (c) vitamin C contents (mg/100 g) and (d) titrable acidity (%).

Table 3. **Mean performance of ten quantitative characteristics of five parents and their 10 F_1 lines of tomato.**

Genotypes	D50%F	PH	NSB	NFC	NFP	SFW	FD	FL	DFH	YPP
Parents										
BT-8	25.67 b	92.40ef	7.67g	4.98gh	27.00 h	91.74cd	63.60ab	56.83ab	83.00 c	1.34f
BT-15	23.00cd	89.40fg	6.07 h	5.84d	27.27 h	100.18a	53.68ef	59.34a	76.67d	1.92e
BT-14	27.00ab	117.47a	5.60i	5.61de	32.68gh	89.56cde	54.96def	49.89cd	82.67c	2.16cde
BT-11	21.33de	97.66c	7.67g	11.67a	217.25a	8.00k	21.40i	25.25f	72.00e	1.08g
BT-3	27.67a	90.27efg	8.74c	5.17efgh	31.20gh	92.08cd	56.25def	49.92cd	84.00c	2.30c
F_1 Hybrids										
BT-8 × BT-15	22.33cd	96.80cd	8.50d	4.87gh	47.87f	67.55g	52.78f	47.06d	66.33f	2.97ab
BT-8 × BT-14	23.67c	111.53b	7.70g	5.55def	62.47d	84.17ef	67.35a	57.79ab	80.33cd	2.84b
BT-8 × BT-11	21.67de	87.93g	9.10b	8.50b	155.95b	18.70ij	33.12g	32.73e	66.33f	2.16cde
BT-8 × BT-3	26.33ab	87.67g	9.00b	5.32defg	29.96h	55.55h	53.82ef	51.50c	80.67cd	1.20fg
BT-15 × BT-14	22.67cd	111.73b	7.93f	5.31defg	36.13g	97.70ab	59.61bcd	55.81b	82.00c	2.24cd
BT-15 × BT-11	20.00e	98.33c	11.00a	7.63c	114.43c	17.60j	26.53h	31.28e	66.33f	2.07cde
BT-15 × BT-3	23.00cd	93.60de	7.93f	4.58h	48.97f	83.48f	59.43bcd	50.57c	88.33b	3.18a
BT-14 × BT-11	28.00a	111.30b	8.24e	5.54def	43.60f	93.62bc	63.20abc	60.12a	92.67a	2.31c
BT-14 × BT-3	27.00ab	120.32a	5.61i	5.07efgh	36.53g	87.30def	58.41cde	50.86c	81.00c	2.29c
BT-11 × BT-3	22.00cd	98.87c	11.03a	8.61b	109.77c	23.04i	34.81g	33.62e	67.00f	1.99de
CV (BHT-4)	25.67b	86.67g	6.12h	5.80d	55.67e	56.45h	58.32de	48.62cd	80.33cd	2.12cde
Mean	24.19	99.48	7.80	6.25	67.30	66.67	51.08	47.51	78.10	2.14
Maximum	28.00	120.32	11.03	8.50	217.25	100.18	67.35	60.12	92.67	3.18
Minimum	20.00	86.67	5.61	4.58	27.00	8.00	21.40	25.25	66.33	1.08
LSD	1.89	3.63	0.21	0.61	5.92	5.41	4.83	3.37	4.28	0.26
CV%	4.69	2.19	1.56	5.90	5.28	4.87	5.67	4.25	3.29	7.28
SE (±)	0.655	1.258	0.072	0.213	2.051	1.873	1.674	1.166	1.481	0.089

Note: D50%F=Days of 50% flowering; PH=Plant height (cm); NSB=Number of secondary branches, NFC=Number of fruits per cluster; NFP=Number of fruits per plant; SFW=Single fruit weight (g); FD=Fruit diameter (mm); FL=Fruit length (mm); DFH=Days of first harvesting; YPP= Yield per plant (kg).

Cluster analysis

The genetic improvement of yield and other agronomic traits largely depends on the genetic distance between the parental lines, as more diverse parents produce vigorous hybrids and subsequent generations (Snehi et al., 2023). The constructed dendrogram visualized that the 10 hybrids and their 5 respective parents were separated into four distinct clusters (Fig. 2). Within the clusters, three hybrids BT-15 × BT-14, BT-14 × BT-11, BT-14 × BT-3, BT-8 × BT-14 and one parent BT-14 were included in cluster I, and the accessions included in this cluster exhibited the maximum number of secondary branches, number of fruits per cluster, number of fruits per plant, vitamin C, brix content, titrable acidity, and also showed short duration for 50% flower initiation and days to first fruit harvest (Table 4). Again, cluster II contained three parents, BT-3, BT-8, BT-15, and three hybrids, BT-8 × BT-15, BT-8 × BT-3, BT-15 × BT-3, which showed promising agronomic characters, viz., single fruit weight, fruit diameter, fruit length, and number of locules per fruit. However, cluster III included only one parent BT-11 due to its distinct features, such as shorter plant height, higher yield per plant, thick skin, and longer shelf-life. Furthermore, three hybrids, BT-8 × BT-11, BT-11 × BT-3, and BT-15 × BT-11 were clubbed in cluster IV, which had moderate performance in terms of single fruit weight, fruit diameter, fruit length, and skin thickness. Similarly, Rahimi et al. (2022) and Verma et al. (2023) employed clustering analysis to determine genetic distances among tomato accessions and suggested that genetic distances obtained through clustering can be used to exploit high-heterotic groups in hybridization programs. In the current study, the cluster distance demonstrated that cluster I had the maximum intra-cluster distances, suggesting that populations included in this cluster were highly heterogeneous (Fig. 3). However, the highest inter-cluster distances were noted between cluster I and cluster II, preceded by cluster II and cluster III, indicating that populations under these clusters had the highest genetic variability among themselves. This may be due to the involvement of diverse parents in the hybrid combinations. Therefore, it is expected that segregating populations can be obtained from these hybrids through recurrent selection in future breeding programs to develop superior tomato varieties.

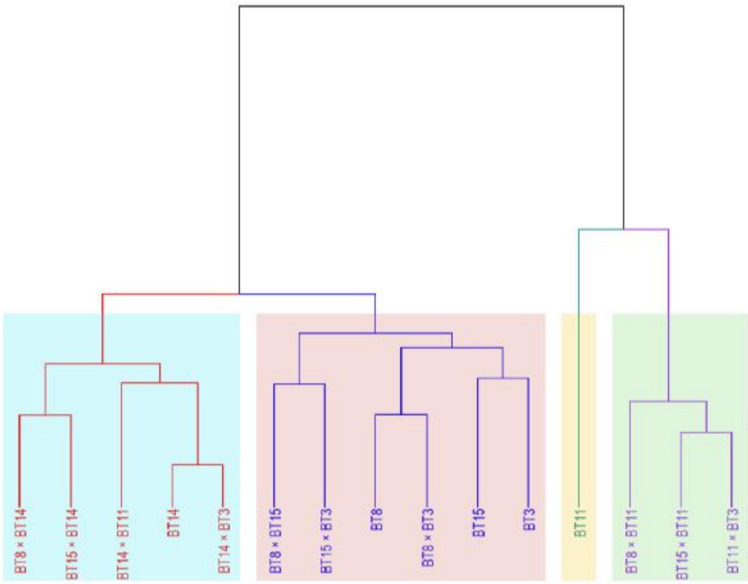

Fig. 2. Dendrogram showing the genetic relationships among hybrids and their parental lines, grouped into four distinct clusters based on their similarity. Here, light blue color indicated cluster I, light pink indicated cluster II, light yellow indicated cluster III and light green indicated cluster IV.

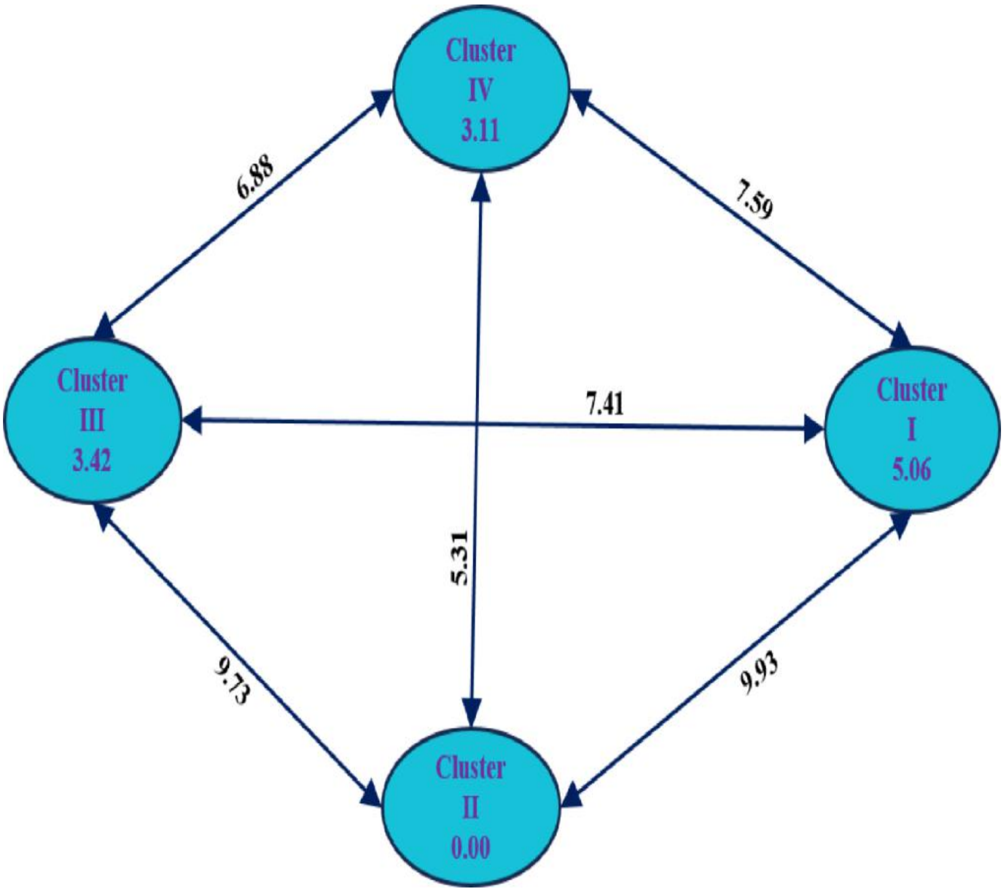

Fig. 3. Intra- and inter-cluster distances among the four clusters derived from hierarchical cluster analysis.The ellipses represent the four clusters (I–IV), with values inside each ellipse indicatingintra-cluster distances(within-cluster genetic divergence), and the arrows showing inter-cluster distances (genetic divergence between clusters).

Table 4. Average cluster mean values for the sixteen traits of four clusters.

Clusters	D50%F	PH	NSB	NFC	NFP	SFW	FD	FL	DFH	YPP	NL	ST	SL	VC	BRIX	TA
Cluster I	21.25	95.70	9.70	9.10	149.35	16.84	28.97	30.72	67.92	1.83	2.50	2.13	16.09	44.69	5.23	0.29
Cluster II	25.67	114.47	7.02	5.41	42.25	90.47	60.71	54.89	83.73	2.37	4.73	3.85	14.53	10.24	4.65	0.06
Cluster III	22.67	95.20	8.22	4.73	48.42	75.52	56.11	48.82	77.33	3.08	3.50	4.77	24.50	16.64	3.50	0.07
Cluster IV	25.67	89.94	7.87	7.87	28.86	84.89	56.84	54.40	81.09	1.69	3.83	4.06	15.59	16.23	4.55	0.09

Note: D50%F=Days of 50% flowering; PH=Plant height (cm); NSB=Number of secondary branches, NFC= Number of fruits per cluster; NFP= Number of fruits per plant; SFW=Single fruit weight (g); FD=Fruit diameter (mm); FL=Fruit length (mm); DFH=Days of first harvesting; YPP= Yield per plant (kg), NL = Number of locules per fruit, ST = Skin thickness (mm), SL = Shelf-life duration (Days after harvesting), VC = Vitamin C (mg/100g), Brix content and TA = Titrable acidity (%).

Genetic parameters among the variables

In crop improvement programs, genetic variation determination is a crucial step for estimating breeding values, aiding in selecting important yield-contributing traits. Regarding these, variability components viz. phenotypic and genotypic coefficient of variance, heritability, and genetic advance (%) provide reliable selection methods in breeding programs (Rasheed et al., 2022). In the present study, all the studied traits possessed a higher phenotypic coefficient of variance than their genotypic counterparts (GCV). In contrast, the minimal fluctuation between PCV and GCV implied that genes that regulated the heredity of these traits were greatly influenced by genetic factors (Fig. 4a). Moreover, the major percentage of the traits, excluding days to 50% flowering, plant height, number of secondary branches, days to first fruiting, and brix percentage, had a higher genotypic coefficient variation (variance> 20), indicating the existing variance among these traits facilitated an enormous scope to develop improved tomato cultivars by selecting these traits. Previously, Singh et al. (2017) and Hussain et al. (2021) also reported similar ranges of variability across different tomato accessions.

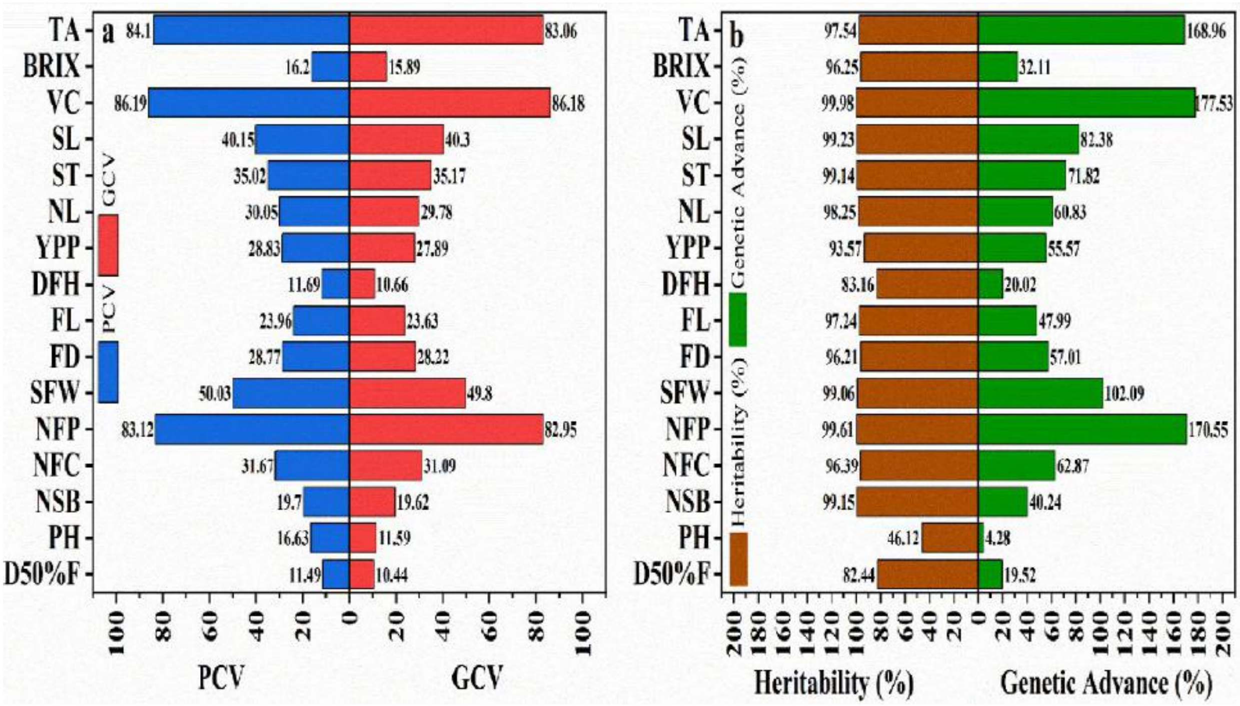

Fig. 4. (a) **Phenotypic and genotypic coefficient of variance, (b) broad sense heritability (%) and genetic advancement (%) for the selected eighteen variables among the hybrids and parents.**

Note: D50%F=Days of 50% flowering; PH=Plant height (cm); NSB=Number of secondary branches, NFC= Number of fruits per cluster; NFP= Number of fruits per plant; SFW=Single fruit weight (g); FD=Fruit diameter (mm); FL=Fruit length (mm); DFH=Days of first harvesting; YPP= Yield per plant (kg), NL = Number of locules per fruit, ST = Skin thickness (mm), SL = Shelf-life duration (Days after harvesting), VC = Vitamin C (mg/100g), Brix content and TA = Titrable acidity (%).

In tomato breeding programs, selecting traits to formulate feasible breeding strategies based on heritability and genetic advance is a well-recognized biometric tool. Heritability defines the degree of inheritance from the progenitors to the offspring, whereas genetic advance determines the effectiveness of selection (Pooja et al., 2022). Therefore, selecting suitable traits based on heritability and genetic advance is more predictable than heritability alone. Interestingly, all the studied traits except plant height (46.12 and 4.28%) showed a higher broad sense heritability accompanied by a higher genetic advance in percentage of mean (Fig. 4b). However, traits viz. the number of fruits per plant (99.61 and 170.55), single fruit weight (99.06 and 102.09), vitamin C content (99.98 and 177.53) and titrable acidity (97.54 and 168.96) exhibited the highest percentage of heritability and genetic advance. Similarly, the preponderance of high heritability and genetic advance for yield-attributing and nutritional traits was also reported by Anuradha et al. (2020) and Zannat et al. (2023). Therefore, consideration of these traits will be effective in selecting appropriate breeding lines to develop high-yielding tomato cultivars.

Linear relationship among the pairwise traits with fruit yield

Tomato fruit yield is a complicated trait reflecting the interaction of multiple genes that also govern the expression of other traits. Therefore, the association between the traits and fruit yields needs to be assessed in fabricating an efficient selection strategy. Correlation analysis aids breeding programs by identifying pairwise relationships among traits, enabling breeders to select the most important traits for future genetic improvement and to enhance yield performance. Falconer (1981) stated that the changes in one trait can significantly alter the performance of other traits. In the current study, Pearson correlation analysis among the yield-attributing traits with fruit yield was estimated (Fig. 5). The association among the pairwise traits revealed that fruit yields had a positive and strong interrelationship with fruit diameter (0.39**), number of secondary branches (0.44**), single fruit weight (0.34*) and skin thickness (0.35*). Therefore, selecting these traits will be rewarded, as their improvement simultaneously increases fruit yield. Furthermore, fruit length (0.26), days to first fruit harvest (0.12), and plant height (0.05) also exerted positive, but weak influences on fruit yield. Similar associations with fruit yield were also suggested by Reddy et al. (2013) and Sushma et al. (2020). Among the yield-contributing traits, days to 50% flowering (-0.06) and number of fruits per plant (-0.30) showed negative correlations with fruit yield, traits that should be improved in the next breeding programs.

As a fleshy vegetable, the preservation capabilities and nutritional properties of tomatoes greatly depend on post-harvest qualities. The current findings revealed that skin thickness exhibited a significant positive association with the number of locules per fruit (0.48***), fruit length (0.71**), fruit diameter (0.65***) and single fruit weight (0.67***). At the same time, skin thickness also showed a positive linear relationship with shelf-life duration (0.18). These associations suggest that thicker skin not only improves the yield of contributing traits but also extends shelf-life. On the other hand, brix content, vitamin C, and titrable acidity similarly showed strong interrelationship with each other and had a positive association with shelf-life, suggesting that longer shelf-life maintains intact nutritional qualities by reducing deterioration in tomato quality after harvesting. However, nutritional qualities such as vitamin C, brix content, and titrable acidity showed strong negative correlations with days to first fruit harvest, indicating that extended harvesting periods greatly decreased the health benefits of the tomato. This may be due to environmental fluctuations that trigger unfavorable conditions, *viz.*, higher transpiration, respiration, and ethylene production, deteriorate nutritional properties (Thole et al., 2021). Considering the above findings, we can conclude that improvements in qualitative traits should also be addressed in tomato breeding programs.

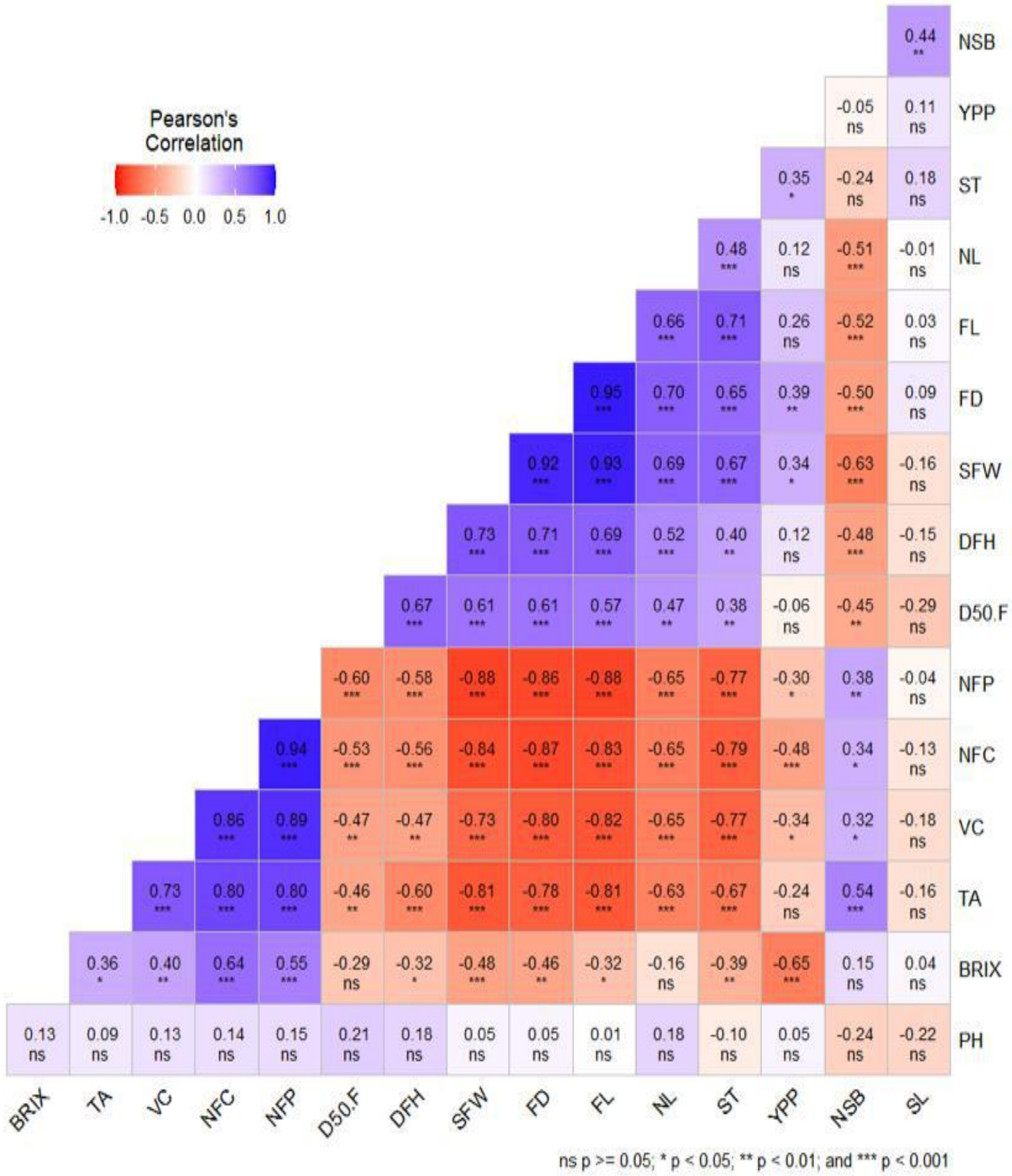

Fig. 5. Correlation coefficient among the different pairs of quantitative traits with fruit yields.

Note: D50%F=Days of 50% flowering; PH=Plant height (cm); NSB=Number of secondary branches, NFC= Number of fruits per cluster; NFP= Number of fruits per plant; SFW=Single fruit weight (g); FD=Fruit diameter (mm); FL=Fruit length (mm); DFH=Days of first harvesting; YPP= Yield per plant (kg), NL = Number of locules per fruit, ST = Skin thickness (mm), SL = Shelf-life duration (Days after harvesting), VC = Vitamin C (mg/100g), Brix content and TA = Titrable acidity (%).

Direct and indirect effects on the fruit yields

Path coefficient analysis partitions the contribution of yield-related traits into direct and indirect effects, enabling breeders to identify the most influential yield components and develop targeted selection strategies for improved productivity. Our current findings indicated that the number of secondary branches (0.59), the number of fruits per plant (0.95), single fruit weight (0.87), fruit diameter (0.94), and skin thickness (0.10) showed the most potent positive direct effects on fruit yield, underscoring that fruit quality related traits exerted significant contribution in overall yield improvement (Table 5). These traits reinforce each other through positive indirect effects; for example, single fruit weight and fruit diameter influence tomato quality via vitamin C content (0.93 and 0.90), BRIX percentage (0.15 and 0.15) and total tritrable acidity (0.28 and 0.27), augmenting its overall correlation with fruit yield (0.34* and 0.39**, respectively) and thereby improving the overall fruit yield production. On the other hand, despite the number of fruits per plant having a negative correlation with fruit yield (-0.30*), this trait indirectly enhances tomato yield production through the positive contribution of fruit length (0.94), days to first fruit harvesting (0.38) and the number of secondary branches (0.23). This indicates a trade-off between fruit number and size, where indirect trait effects can counterbalance direct negative associations and support better fruit development. Similarly, Jogi et al. (2018) and Madhavi et al. (2019) reported that fruit width, fruit length, and average fruit weight are critical yield contributors, as evidenced by correlations and path analysis studies. On the other hand, the number of fruits per cluster (-0.83), fruit length (-0.95), days to first fruit harvest (-0.60), and number of locules (-0.39) manifested strong adverse direct effects. However, these traits can also enhance the fruit yield production through the contribution of other characteristics. For instance, the number of fruits per cluster can indirectly improve the yield performance via the number of secondary branches (0.21), number of fruits per plant (0.91), fruit length (0.94), and number of locules per fruit (0.26). Additionally, fruit length can indirectly improve yield performance via the number of fruits per cluster (0.72), single fruit weight (0.92), and fruit diameter (0.93). Similar trends in enhancing fruit yield via other traits were also reported by Kumar et al. (2014) and Tandel et al. (2023). Conversely, several quality-related characteristics, including higher vitamin C content (-0.98), BRIX content (-0.31), and titratable acidity (-0.34), were found to exert adverse direct effects on yield. This indicates that while these traits enhance fruit quality, they may divert assimilates and metabolic resources away from fruit biomass accumulation, thereby reducing overall yield. Therefore, balancing between yield-contributing and nutritional traits improvement is a critical research area in tomato breeding programs. Similar negative associations between nutritional quality and fruit yield have been reported by Anuradha et al. (2018). Nonetheless, the positive interrelationships among these quality attributes contribute substantially to improving overall fruit quality. These results emphasize that selection strategies in tomato breeding should prioritize traits with strong positive direct or indirect effects on yield, while simultaneously incorporating post-harvest and nutritional quality traits in a balanced manner. Such an integrated approach would enable the development of tomato cultivars that combine high yield potential with superior market and nutritional value.

Table 5.Direct and indirect effects of fifteen traits on the fruit yields.

Traits	D50%F	PH	NSB	NFC	NFP	SFW	FD	FL	DFH	NL	ST	SL	VC	BRIX	TA	Correlation with fruit yield
D50%F	**0.16**	-0.06	-0.29	0.49	-0.67	0.75	0.84	-0.85	-0.50	-0.21	0.04	0.08	0.66	0.11	0.17	-0.06
PH	0.09	**-0.12**	-0.44	-0.30	0.63	0.34	0.27	-0.04	-0.35	-0.17	-0.03	0.16	-0.46	-0.11	-0.09	0.05
NSB	-0.08	0.09	**0.59**	-0.29	0.54	-0.70	-0.73	0.72	0.32	0.20	-0.02	-0.12	-0.41	-0.05	-0.19	-0.05
NFC	-0.09	-0.04	0.21	**-0.83**	0.91	-0.78	-0.88	0.94	0.37	0.26	-0.08	0.04	-0.50	-0.21	-0.28	-0.48***
NFP	-0.10	-0.05	0.23	-0.80	**0.95**	-0.82	-0.87	0.94	0.38	0.26	-0.08	0.01	-0.97	-0.18	-0.28	-0.30*
SFW	0.11	-0.02	-0.38	0.71	-0.88	**0.87**	0.90	-0.94	-0.47	-0.27	0.07	0.04	0.93	0.15	0.28	0.34*
FD	0.11	-0.02	-0.30	0.75	-0.87	0.91	**0.94**	-0.95	-0.47	-0.29	0.07	-0.03	0.90	0.15	0.27	0.39**
FL	0.10	0.00	-0.31	0.72	-0.90	0.92	0.93	**-0.95**	-0.46	-0.27	0.07	-0.01	0.85	0.10	0.28	0.26
DFH	0.13	-0.07	-0.32	0.51	-0.74	0.71	0.85	-0.88	**-0.60**	-0.22	0.04	0.04	0.65	0.12	0.22	0.12
NL	0.08	-0.05	-0.31	0.56	-0.71	0.70	0.84	-0.85	-0.34	**-0.39**	0.05	0.00	0.83	0.06	0.22	0.12
ST	0.07	0.04	-0.15	0.67	-0.73	0.73	0.86	-0.84	-0.26	-0.19	**0.10**	-0.04	0.92	0.13	0.24	0.35*
SL	-0.05	0.07	0.26	0.11	-0.14	-0.38	0.14	-0.06	0.10	0.01	0.02	**-0.26**	0.23	-0.01	0.06	0.11
VC	-0.08	-0.04	0.19	-0.73	0.89	-0.74	-0.87	0.90	0.31	0.26	-0.08	0.05	**-0.98**	0.13	0.25	-0.34*
BRIX	-0.05	-0.04	0.10	-0.56	0.85	-0.69	-0.68	0.57	0.24	0.07	-0.04	-0.01	0.51	**-0.31**	0.12	-0.65***
TA	-0.08	-0.03	0.32	-0.69	0.87	-0.79	-0.87	0.90	0.40	0.25	-0.07	0.04	0.93	0.11	**-0.34**	-0.24
Residual effects 0.09																

Note: Bold indicates the direct effects of traits on the fruit yield

Conclusion

The present study demonstrated substantial genetic variability among tomato hybrids and their parents for agronomic, post-harvest, and nutritional traits, providing a strong foundation for selection. High heritability coupled with high genetic advance in key yield and quality parameters suggests additive gene action, making direct selection effective. Positive correlations between yield and traits such as fruit diameter, single fruit weight, and skin thickness indicate the potential for simultaneous improvement in productivity and shelf-life. Notably, BT-15 × BT-3, BT-8 × BT-15, and BT-8 × BT-14 excelled inyield performance, while BT-8 × BT-11 and BT-8 × BT-15 combined extended storability with enhanced nutritional content. These results underscore the value of integrating agronomic, post-harvest, and nutritional parameters into breeding strategies to develop tomato varieties that meet both producer and consumer demands.

Acknowledgment

The corresponding author acknowledges the Ministry of Science and Technology, Government of the People’s Republic of Bangladesh, for funding the research project, and Sher-e-Bangla Agricultural University, Dhaka, for logistical support.

Authors contribution

Mr. Niloy Gain and Ms. Mahbuba Fatema were responsible for conducting the experiments, analyzing the data, and drafting the manuscript. Dr. Jamilur Rahman supervised the research, contributed

to the experimental design, facilitated the required resources, and revised the manuscript.

Conflict of interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Anuradha B, Saidaiah P, Reddy K, Harikishan S and Geetha A. Genetic variability, heritability and genetic advance for yield and yield attributes in tomato (*Solanum lycopersicum* L.). *Int. J. Curr. Microbiol. Appl. Sci.* 2020; 9: 2385-2391.

Anuradha B, Saidaiah P, Sudini H, Geetha A and Reddy KR. Correlation and path coefficient analysis in tomato (*Solanum lycopersicum* L.). *J. Pharmacogn. Phytochem.* 2018; 7(5): 2748-2751.

BARI Handbook 2017. *Krishi Projukti Hatboi* (Handbook on Agro-technology). 7th edition, Bangladesh Agricultural Research Institute (BARI), 2017.

Dewey DR and Lu KH. A correlation and path-coefficient analysis of components of crested wheatgrass seed production. *Agron. J.* 1959; 51(9): 515-518.

Falconer DS. *Introduction to quantitative genetics*. 2nd ed. Oliver and Boyd, Edinburgh and London. 1981; pp. 164-176.

Farwah S, Afroza B, Rashid R, Dar ZA and Khan I. Mean performance of parents and their crosses in tomato (*Solanum lycopersicum* L.) for qualitative traits. *Pharma Innov. J*. 2023; 12(3): 3697-3701.

FAOSTAT (Food and Agriculture Organization of the United Nations Statistical Database). *Crops and Livestock Products*, Rome, 2023.

Gonzalez-Vega JC, Fougere C, Garcia-Casal MN and Pena-Rosas JP. Nutritional and health benefits of tomatoes: A review. *Food Chem.* 2021; 343: 128547.

Hosen M, Rafii MY, Mazlan N, Jusoh M, Farhana M and Chowdhury N. Estimation of heterosis and combining ability for improving yield, sweetness, carotenoid and antioxidant qualities in pumpkin hybrids (*Cucurbita moschata* Duch. Ex Poir.). *Horticulturae*, 2022; 8(10): 863.

Hussain K, Lone S, Malik A, Masoodi KZ, Dar Z and Nazir N. Genetic variability studies in cherry tomato for growth, yield, and quality traits in open field conditions. *Int. J. Agric. App. Sci.* 2021; 2(2): 60-64.

Islam MT, Hossain MM and Rahman MS. Evaluation of hybrid tomato varieties for yield and shelf life in Bangladesh. *Bangladesh J. Agric. Res.* 2021; 46(3): 517-527.

Jogi M, Lingaiah HB, Indiresh KM, Singh TH, Samuel DK and Ramachandra RK. Studies on correlation and path coefficient analysis in tomato (*Solanum lycopersicum* L.). *Int. J. Chem. Stud.* 2018; 6(5): 1499-1502.

Johnson HW, Robinson HF and Comstock RE. Estimates of genetic and environmental variability in soybeans. *Agron. J.* 1955; 47(7): 314-318.

Kumar P, Ram C, Singh M and Saini S. Studies on analysis of variance and mean performance of parents and their crosses among various quantitative traits in tomato (*Solanum lycopersicum*). *Int. J. Chem. Stud.* 2020; 8(1): 1992-2003.

Kumar R, Ram CN, Yadav GC, Deo C, Vimal C and Bhartiya HD. Studies on correlation and path coefficient analysis in tomato (*Solanum lycopersicum* L.). *Plant Arch*. 2014; 14(1): 443-447.

Kumar R. Performance of tomato (*Solanum lycopersicum* L.) genotypes for growth, yield and quality. *Ann. Plant Soil Res*. 2021; 23(4): 465-468.

Lin T, Zhu G, Zhang J, Xu X, Yu Q, Zheng Z and Huang S. Genomic analyses provide insights into the history of tomato breeding. *Nat. Genet.* 2014; 46(11): 1220-1226.

Madhavi Y, Reddy RVSK, Kumar SS and Reddy CS. Correlation and path analysis studies for yield and quality traits in tomato (*Solanum lycopersicum* L.). *Int. J. Pure App. Biosci.* 2019; 7(1): 306-312.

Meena RK, Sanjay K, Meena ML and Shashank V. Genetic variability, heritability and genetic advance for yield and quality attributes in tomato (*Solanum lycopersicum* L.). *J. Pharmacog. Phytochem*. 2017; 7: 1937–1939.

Panse VG and Sukhatme PV. *Statistical Methods for Agricultural Workers*. 2nd ed., *Indian Council of Agricultural Research, New Delhi*, 1967.

Pooja H, Gasti VD, Bhavidoddi A, Yashavantakumar H, Prashantha A and Srikantaprasad D. Genetic variability, heritability and genetic advance in determinate types of tomato (*Solanum lycopersicum* L.). *Pharm. Innov. J.* 2022; 11(4): 222-225.

Rahimi S, Alam K, Ahmad M, Sharma K, Keshari D and Wamiq M. Assessment of genetic divergence in tomato (*Lycopersicon esculentum* Mill) genotypes. *Int. J. Environ. Clim. Chang.* 2022; 12(3): 1-7.

Rasheed A, Ilyas M, Khan TN, Mahmood A, Riaz U and Chattha MB. Study of genetic variability, heritability, and genetic advance for yield-related traits in tomato (*Solanum lycopersicum* MILL.). *Front. Genet*. 2022; 13: 1-13.

Reddy RB, Reddy MP, Reddy DS and Begum H. Correlation and path analysis studies for yield and quality traits in tomato *(Solanum lycopersicum L.). J. Agri. Vet. Sci.* 2013; 4(4): 56-59.

Singh A, Ram C, Yadav G, Srivastava R, Deo C and Gautam D. Studies on genetic variability, heritability and genetic advance in tomato (*Solanum lycopersicum* L.). *Int. J. Pure App. Biosci.* 2017; 5: 908-912.

Sinha R, Singh R and Singh A. Postharvest management and processing of tomato. *Food Rev. Int*. 2019; 35(4): 375-397.

Snehi S, Prakash NR, Pant U, Singh PK, Kumar S, Jeena AS and Bhajan R. Prediction of heterotic combinations using correlation between genetic distance, heterosis and combining ability in yellow sarson (*Brassica rapa* var. yellow sarson Prain). *Vegetos.* 2023; 37(4): 1552-1564.

Sushma K, Saidaiah P, Reddy RK, Sudini H and Geetha A. Correlation and path coefficient analysis in tomato (*Solanum lycopersicum* L.). *Int. J. Curr. Microbiol. App. Sci.* 2020; 9(11): 2569-2575.

Tandel T, Rathod D, Sarkar M, Emmi S, Chaudhari BN and Tank RV. Studies on correlation and path coefficient analysis in tomato (*Solanum lycopersicum* L.). *Pharma Innov. J.* 2023; 12(12): 2785-2788.

Tee ES, Young SI, Ho SK and Mizura SS. Determination of vitamin C in fresh fruits and vegetables using the dye-titration and microfluorometric methods. Pertanika *J. Trop. Agric. Sci.* 1988; 11(1): 39-44.

Thole V, Vain P and Martin C. Effect of elevated temperature on tomato post-harvest properties. *Plants.* 2021; 10(11): 2359.

Verma B, Sharma D and Patel JK. Assessment of genetic diversity in tomato (*Solanum lycopersicum* L.) genotypes using cluster and principal component analysis. *Pharma Innov. J.* 2023; 12(6): 5014-5019.

Zannat A, Hussain MA, Abdullah AH, Hossain MI, Saifullah AM and Sathi FA. Exploring genotypic variability and interrelationships among growth, yield, and quality characteristics in diverse tomato genotypes. *Heliyon*, 2023; 9(8): e18958.