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# GENETIC ANALYSIS AND HETEROTIC STUDIES IN TOMATO (*SOLANUM LYCOPERSICUM* L.) HYBRIDS FOR FRUIT YIELD AND ITS RELATED TRAITS

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## SUMMARY

A study was conducted to determine the types of gene action of different yield-related traits in tomato and the combining ability in four advanced lines. The heterotic response in tomato hybrids was also assessed. Analysis of variance (ANOVA) revealed significant differences ($P \leq 0.05$) among all the traits. General combining ability (GCA) and specific combining ability (SCA) for all chosen traits were computed using Griffing's approach of diallel. Combining ability revealed the additive and non-additive genetic effects for all selected traits of advanced lines. T-1360 was found as a good general combiner for the number of cluster plant$^{-1}$, average fruit weight, number of flowers cluster$^{-1}$, fruit length, number of fruit cluster$^{-1}$, and yield. The variance of the GCA to SCA ratio was found less than 0.5 for each trait, which confirmed the presence of non-additive gene action. The results revealed higher magnitudes of phenotypic coefficient of variance (PCV) than the genotypic coefficient of variance (GCV). The high magnitudes of heritability (72% to 92%) and genetic advance (36.63% to 139.72%) were found for the number of cluster plant$^{-1}$, average fruit weight (g), the number of fruits cluster$^{-1}$, and yield. Among all crosses, the cross ST-100 × T-1360 showed maximum positive heterosis over the mid parent (566.6%) and the better parent (455.5%). The identified tomato genotypes can be used further in different tomato breeding programs to improve fruit yield and other yield-related traits.

**Keywords:** GCA and SCA, heritability, heterosis, *Solanum lycopersicum* L.

**Key findings:** Heterosis breeding is proven to be an excellent approach for enhancing the yield and earliness of tomato hybrids. However, traits, e.g., number of clusters plant$^{-1}$, number of fruit cluster$^{-1}$, and average fruit weight, can be considered the main traits for improving the yield of tomato. The direction of selection can be assessed by the genetic action of a particular trait.

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## INTRODUCTION

Globally, tomato (*Solanum lycopersicum* L.) is recognized as the second most important vegetable crop after potato (Naveed *et al*., 2019). The cleistogamous nature of its flower makes it highly self-pollinated. Tomato evolved in Peru (Narasimhamurthy and Gowda, 2013) and belongs to the family, *Solanaceae* with chromosome number 2*n* = 24. It is widely adaptable and can be grown in all climatic regions of the world (Rashid *et al.,* 2016). With time, market demands for tomato increasing day by day due to their huge consumption all over the world (Atif *et al.,* 2015). Around the world, it is used almost daily, whether cooked with chicken, beans, vegetables, mutton, and beef. It is also consumed as a puree, ketchup, and salad (Saleem *et al.,* 2013; Ramzan *et al*., 2014; Rai *et al*., 2016). Tomato also possessed medicinal properties; its consumption lowers the risk of cardiovascular diseases. The carotenoids found in tomato are antioxidant and antiproliferative, which helps to prevent the formation of cancer in the human body (Campestrini *et al.,* 2019). Likewise, tomato is a good source of lycopene, vitamin A, vitamin C, and minerals that protect the skin from damage caused by ultra-violet (UV) light (Sekhar *et al.,* 2010).

Normally, a tomato variety produces about 16–25 t/ha of fruit yield, whereas the hybrid tomato gives 60 to 80 t/ha (Sunil, 2013). In 2019, the tomato was cultivated as *kharif* (summer) crop in Pakistan on 16,930 ha of land while 38,330 ha were sown during *rabi* (winter) season with a fruit yield of 14,757 and 41,372 tons, respectively (GOP 2019). The tomato yields are low in Pakistan as compared with the world. The unpredictable production of tomato through the years is due to less availability of quality seeds, and less genotype selection for different biotic and abiotic stresses, which are the major reasons for its lower yield in Pakistan. To meet the increasing demand for tomato in the market, breeders need to develop high-yielding genotypes of tomatoes. Remarkable progress has been achieved by the breeders after the development of high-yielding hybrids in tomatoes (Kurian *et al.,* 2001; Ahmad *et al.,* 2011; Shende *et al*., 2012; Kumar *et al*., 2015b).

For genetic improvement, the knowledge about general combining ability (GCA) and specific combining ability (SCA) is very useful. The GCA and SCA values do not depend only on the gene effects; it also relies on the gene structure of the parents involved in crossing (Kaushik and Dhaliwal, 2018). Combining ability studies not only delivers suitable information regarding diverse parent selection related to the performance of different hybrid combinations but also explain different types of gene actions (Savale *et al.,* 2017). GCA effect is useful for picking a good combiner parent while SCA effect points out best cross combinations (Farzane *et al.,* 2012).

The high value of GCA variance is an indication of additive gene action, but greater SCA variance reveals the maximum contribution of non-additive genes (Chauhan *et al.,* 2014; Akram *et al.,* 2019). For the identification of the desirable hybrid combinations and study of their combining abilities, i.e., GCA and SCA in tomato diallel mating design by Griffing is a very popular technique (Rego *et al*., 2009). Saleem *et al.* (2013) used morphological characters, such as, days to 50% maturity, fruit length, plant height, single fruit weight, fruit width, and yield plant$^{-1}$, to assess the hybrid vigor in determinate tomato. The study to identify the parents and hybrid combinations in tomato, with desirable SCA and GCA effects through diallel mating design, was performed to see the nature of gene action leading to the inheritance of particular plant traits.

## MATERIALS AND METHODS

### Experiment site

The research was conducted during the years 2019–20 at the Horticultural Research Institute, National Agricultural Research Centre, (HRI-NARC), Islamabad-Pakistan. The site was situated at 73.08° longitude, 33.42° latitude with an elevation of 683 MSL (mean sea level).

### Experimental design and plant material

The four advanced lines (KHT-103, KHT-107, ST-100, and T-1360) used in the experiment were obtained from the Asian Vegetable Research and Development Center (AVRDC), Taiwan. The study was executed by following full-diallel crossing scheme to make all possible cross combinations for hybrid development shown in Table 1. The $F_1$ hybrids, with their parents, were tested using a randomized complete block design with three replications. The study managed the row-to-row and plant-to-plant distances at 75 and 50 cm,

**Table 1.** Diallel crossing scheme for breeding of four advanced lines of tomato.

| Genotypes | KHT-103 | KHT-107 | ST-100 | T-1360 |
|---|---|---|---|---|
| KHT-103 | KHT-103 × KHT-103 | KHT-103 × KHT-107 | KHT-103 × ST-100 | KHT-103 × T-1360 |
| KHT-107 | KHT-107 × KHT-103 | KHT-107 × KHT-107 | KHT-107 × ST-100 | KHT-107 × T-1360 |
| ST-100 | ST-100 × KHT-103 | ST-100 × KHT-107 | ST-100 × ST-100 | ST-100 × T-1360 |
| T-1360 | T-1360 × KHT-103 | T-1360 × KHT-107 | T-1360 × ST-100 | T-1360 × T-1360 |

Diagonal; selfed, above diagonal; direct crosses, below diagonal; reciprocals/indirect crosses

respectively. Likewise, all recommended agronomic and cultural practices were adopted during the cropping season.

### Measured plant traits

The evaluation of parents and their hybrids was performed in the field. Different plant traits were selected for the screening of the genotypes viz., days to flowering, days to maturity, number of flowers cluster$^{-1}$, number of fruits cluster$^{-1}$, single fruit weight (g), number of flowers cluster$^{-1}$, number of clusters plant$^{-1}$, plant height (cm), fruit length (cm), fruit width (cm), and yield (kg plant$^{-1}$).

### Data analysis

The Recorded data were subjected to an ANOVA test using Statistix 8.1 software, and a comparison of mean values was performed at a 5% probability level using Tukey's test (Steel *et al.,* 1997). The relationship among measured traits was determined using Pearson's correlation technique as explained by You *et al.* (1996) and followed by Keppler (2017). The analysis of combining ability was carried out according to Griffing's method (Griffing, 1956) as conducted by Murtadha *et al.* (2018).

## RESULTS AND DISCUSSION

### Means comparison

The results of the analysis of variance (ANOVA) exposed significant variation among all the recorded characteristics, which explained the occurrence of genetic variability among them that can be used for screening of tomato hybrids (Table 2). The mean performance of 12 tomato hybrids, along with their parents, is presented in Table 3. The average fruit weight (g) ranged from 44.17 to 103.37 g. Hybrids ST-100 × T-1360 (103.37 g) showed the highest average fruit weight among all other hybrids. The number of clusters plant$^{-1}$ varied from 20 to 37; ST-100 × T-1360 showed the maximum number of cluster plant$^{-1}$ i.e. 37. The days to 50% flowering diverged from 52 to 67 days; hybrid ST-100 × KHT-103 (52 days) was found early flowering, whereas hybrid ST-100 × KHT-107 (67 days) was found late flowering. Patwary *et al.* (2013) and Chauhan *et al.* (2014) also reported early flowering in tomato hybrids. The days to maturity varied from 103 to 116.67 days; hybrid KHT-103 × T-1360 was found early maturing at 103 days, whereas hybrid KHT-103 x ST-100 (116.67 days) was observed late maturing. Kumar *et al.* (2012) also discussed the presence of early maturity among hybrids in their findings. The number of flowers cluster$^{-1}$ varied from 4.67 to 7.47; hybrid ST-100 × T-1360 produced the highest number of flowers cluster$^{-1}$ (7.47). Fruit length (cm) varied from 5.12 to 7.80 cm; hybrid ST-100 × T-1360 delivered maximum fruit length among all other screened hybrids. The number of fruits cluster$^{-1}$ ranged from 2.0 to 5.77; hybrid ST-100 × T-1360 was found with the highest number of fruits in a single cluster. Garg and Cheema (2010) also described improvement in fruit cluster$^{-1}$ between tomato hybrids. The fruit width ranged from 3.56 to 5.51 cm; hybrid KHT-107 × T-1360 delivered the highest fruit width as compared with other screened hybrids. Plant height ranged from 64.47 to 108.67 cm; hybrid ST-100 × KHT-107 (67.60 cm) was found shortest, whereas hybrid T-1360 × KHT-107 (91.87 cm) was found tallest. Huge variation was observed regarding fruit yield (kg plant$^{-1}$). It ranged from 0.48 to 4.0 (kg plant$^{-1}$); hybrid ST-100 × T-1360 produced the maximum fruit yield (4.0 kg plant$^{-1}$). Joshi and Thakur (2003) also confirmed the enhancement in fruit yield of tomato hybrids as they reported enhanced fruit yield among locally developed tomato hybrids.

### Variances due to GCA and SCA and their effects

The estimates of general combining ability (GCA), which was helpful in the selection of better parents for different breeding plans, are presented in Table 4. Among parents, T-1360

**Table 2.** Analysis of variance for yield and its related traits in tomato.

| Source of variation | d.f. | DM | FC | DF | FTC | CP | PH | AFW | FL | FW | Yield |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Replications | 2 | 1.94 | 0.06 | 4.75 | 0.10 | 2.52 | 4.96 | 37.45 | 0.008 | 0.11 | 0.01 |
| Genotypes | 15 | 55.61** | 1.67** | 52.31** | 3.67** | 80.82** | 371.14** | 820.15** | 1.67** | 0.78** | 3.48** |
| Residuals | 30 | 4.36 | 0.03 | 2.24 | 0.06 | 3.72 | 3.24 | 93.30 | 0.064 | 0.07 | 0.0032 |
| Means | | 110.94 | 5.65 | 60.188 | 3.4729 | 26.64 | 81.82 | 72.97 | 6.5692 | 4.6367 | 1.585 |
| CV (%) | | 1.88 | 2.95 | 2.49 | 7.02 | 7.24 | 2.20 | 13.24 | 3.84 | 5.87 | 3.58 |
| SeM | | 1.2055 | 0.0961 | 0.8639 | 0.1407 | 1.11 | 1.0396 | 5.579 | 0.1456 | 0.1572 | 0.0382 |

** Highly significant ($P \leq 0.01$), *Significant ($P \leq 0.05$), NS Non-significant ($P > 0.05$)
df = degree of freedom, DM = Days to 50% maturity, FC = Number of flowers per cluster, DF = Days to 50% flowering, FTC = Number of fruits per cluster, CP = Number of clusters per plant, PH = Plant height (cm), AFW = Average fruit weight (g), FL = Fruit length (cm), FW = Fruit width (cm), Y = Yield (kg/plant)

**Table 3.** Mean performance of parental genotypes and their hybrids for various traits in tomato.

| Genotypes | AFW | CP | DF | DM | FC | FL | FTC | FW | PH | Yield |
|---|---|---|---|---|---|---|---|---|---|---|
| Parents | | | | | | | | | | |
| KHT-103 | 74.17 abcde | 27.00 cdef | 57.33 fgh | 112.67 abcd | 4.67 h | 7.80 a | 2.00 h | 3.56 e | 108.67 a | 0.59 ij |
| KHT-107 | 52.17 de | 20.00 g | 60.00 defg | 117.00 a | 5.40 efg | 5.73 fg | 2.27 gh | 4.34 cde | 92.33 b | 0.55 ij |
| ST-100 | 49.17 e | 20.33 g | 63.67 abcd | 115.67 ab | 5.00 gh | 6.24 def | 2.80 fg | 4.79 abcd | 71.73 gh | 0.48 j |
| T-1360 | 72.70 bcde | 30.67 bcd | 62.00 bcde | 109.00 cdef | 5.80 de | 6.29 def | 3.27 f | 4.56 bcd | 64.47 i | 0.72 i |
| Hybrids | | | | | | | | | | |
| KHT-103 x KHT-107 | 44.83 e | 20.33 g | 57.00 gh | 114.67 abc | 4.77 h | 5.12 g | 2.47 gh | 5.39 ab | 87.67 bc | 1.01 h |
| KHT-103 x ST-100 | 81.90 abc | 28.33 cde | 59.33 defg | 116.67 a | 5.80 de | 6.67 cd | 4.03 de | 4.07 de | 79.97 ef | 2.04 e |
| KHT-103 x T-1360 | 73.40 bcde | 26.67 def | 59.33 defg | 103.00 f | 5.60 def | 6.54 de | 3.67 f | 4.59 bcd | 88.30 bc | 1.27fg |
| KHT-107 x KHT-103 | 62.10 cde | 22.00 fg | 54.33 hi | 109.33 bcdef | 4.90 gh | 5.81 efg | 2.80 fg | 4.87 abcd | 85.83 cd | 0.98 h |
| KHT-107 x ST-100 | 83.10 abc | 29.00 bcde | 66.33 ab | 115.00 abc | 6.00 cd | 6.84 bcd | 4.37 cd | 5.12 abc | 68.33 hi | 2.32 d |
| KHT-107 x T-1360 | 71.73 bcde | 24.33 efg | 58.67 efgh | 108.67 cdef | 5.67 de | 6.36 def | 3.00 fg | 5.51 a | 77.13 fg | 1.40 f |
| ST-100 x KHT-103 | 68.77 cde | 24.00 efg | 52.00 i | 111.00 abcde | 5.33 efg | 6.30 def | 3.00 fg | 4.29 de | 80.13 ef | 1.11 gh |
| ST-100 x KHT-107 | 78.67 abcd | 27.33 cdef | 67.00 a | 107.67 def | 5.73 de | 6.61 cd | 3.47 ef | 4.82 abcd | 67.60 hi | 1.35f |
| ST-100 x T-1360 | 103.37 a | 37.00 a | 64.67 abc | 110.00 bcde | 7.47 a | 7.73 a | 5.77 a | 4.13 de | 79.00 f | 4.00 a |
| T-1360 x KHT-103 | 98.33 ab | 34.33 ab | 61.67 cdef | 113.67 abcd | 6.67 b | 7.57 ab | 5.40 ab | 4.46 cd | 84.63 cde | 3.40 b |
| T-1360 x KHT-107 | 63.10 cde | 22.33 fg | 57.00 gh | 105.33 ef | 5.13 fgh | 6.17 def | 2.87 fg | 4.52 cd | 91.87 b | 1.11 gh |
| T-1360 x ST-100 | 90.03 abc | 32.67 abc | 62.67 abcde | 105.67 ef | 6.47 bc | 7.34 abc | 4.80 bc | 5.15 abc | 81.50 def | 3.05 c |
| Range | 44.17–103.37 | 20.00–37.00 | 52.0–67.0 | 103.0-116.67 | 4.67–7.47 | 5.12–7.80 | 2.0–5.77 | 3.56–5.51 | 64.47-108.67 | 0.48–4.0 |

AFW = Average fruit weight (g), CP = Number of clusters per plant, DF = Days to 50% flowering, DM = Days to 50% maturity, FC = Number of flowers per cluster, FL = Fruit length (cm), FTC = Number of fruits per cluster, FW = Fruit width (cm), PH = Plant height (cm), Y = Yield (kg/plant)

**Table 4.** General and specific combining ability effects of parental genotypes and their hybrids for various traits in tomato.

| Genotypes | AFW | CP | DF | DM | FC | FL | FTC | FW | PH | Yield |
|---|---|---|---|---|---|---|---|---|---|---|
| Parents | | | | | GCA Effects of Parents | | | | | |
| KHT-103 | -0.76 | -0.44 | -2.9 | 0.77 | -0.35 | 0.13 | -0.35 | -0.29 | 8.66 | -0.21 |
| KHT-107 | -9.49 | -3.48 | -0.15 | 0.9 | -0.28 | -0.52 | -0.53 | 0.23 | 1.06 | -0.43 |
| ST-100 | 2.55 | 0.73 | 2.23 | 1.23 | 0.2 | 0.18 | 0.41 | 0.01 | -6.82 | 0.27 |
| T-1360 | 7.7 | 3.19 | 0.81 | -2.9 | 0.43 | 0.22 | 0.48 | 0.05 | -2.9 | 0.37 |
| Hybrids | | | | | SCA of Effects of Hybrids | | | | | |
| KHT-103 × KHT-107 | 8.63 | 0.83 | -1.33 | -2.66 | 0.07 | 0.35 | 0.17 | -0.26 | -0.92 | -0.02 |
| KHT-103 × ST-100 | -6.57 | -2.17 | -3.67 | -2.83 | -0.23 | -0.19 | -0.52 | 0.11 | 0.083 | -0.47 |
| KHT-103 × T-1360 | 12.47 | 3.83 | 1.17 | 5.33 | 0.53 | 0.513 | 1.07 | -0.07 | -1.83 | 1.07 |
| KHT-107 × KHT-103 | -9.25 | -1.56 | -1.48 | -0.6 | -0.2 | -0.71 | 0.05 | 0.55 | -4.8 | 0.05 |
| KHT-107 × ST-100 | -2.22 | -0.83 | 0.33 | -3.67 | -0.13 | -0.12 | -0.45 | -0.15 | -0.37 | -0.48 |
| KHT-107 × T-1360 | -4.32 | -1.0 | -0.83 | -1.67 | -0.27 | -0.1 | -0.07 | -0.49 | 7.37 | -0.15 |
| ST-100 × KHT-103 | 0.58 | -0.77 | -3.85 | 0.9 | 0.07 | -0.4 | -0.01 | -0.18 | -3.61 | -0.07 |
| ST-100 × KHT-107 | 14.85 | 4.27 | 4.4 | -1.73 | 0.3 | 0.5 | 0.57 | 0.1 | -8.1 | 0.41 |
| ST-100 × T-1360 | -6.67 | -2.17 | -1 | -2.17 | -0.5 | -0.2 | -0.48 | 0.51 | 1.25 | -0.48 |
| T-1360 × KHT-103 | 5.96 | 1.1 | 2.4 | -0.48 | 0.41 | 0.14 | 0.73 | 0.13 | -1.11 | 0.59 |
| T-1360 × KHT-107 | -3.77 | -3.02 | -3.02 | -1.94 | -0.4 | 0.01 | -0.49 | 0.1 | 4.51 | -0.28 |
| T-1360 × ST-100 | 13.48 | 4.27 | 0.44 | -1.44 | 0.7 | 0.57 | 0.92 | -0.05 | 8.15 | 1.3 |

AFW = Average fruit weight (g), CP = Number of clusters per plant, DF = Days to 50% flowering, DM = Days to 50% maturity, FC = Number of flowers per cluster, FL = Fruit length (cm), FTC = Number of fruits per cluster, FW = Fruit width (cm), PH = Plant height (cm), Y = Yield (kg/plant).

**Table 5.** Variances due to general and specific combining ability for various traits in tomato.

| Source of variation | AFW | CP | DF | DM | FC | FL | FTC | FW | PH | Yield |
|---|---|---|---|---|---|---|---|---|---|---|
| Variance of GCA | 48.24 | 7.51 | 4.59 | 3.58 | 0.14 | 0.12 | 0.27 | 0.04 | 43.57 | 0.15 |
| Variance of SCA | 330.15 | 26.64 | 18.0 | 8.33 | 0.59 | 0.72 | 1.33 | 0.24 | 113.33 | 1.71 |
| Variance of reciprocal | 41.29 | 3.79 | 2.69 | 10.02 | 0.11 | 0.07 | 0.30 | 0.09 | 9.49 | 0.31 |
| Variance of (GCA/SCA) | 0.15 | 0.28 | 0.25 | 0.43 | 0.23 | 0.17 | 0.20 | 0.17 | 0.38 | 0.085 |

AFW = Average fruit weight (g), CP = Number of clusters per plant, DF = Days to 50% flowering, DM = Days to 50% maturity, FC = Number of flowers per cluster, FL = Fruit length (cm), FTC = Number of fruits per cluster, FW = Fruit width (cm), PH = Plant height (cm), Y = Yield (kg/plant).

showed the maximum positive magnitude of GCA for the traits; average fruit weight, number of cluster plant$^{-1}$, number of flower cluster$^{-1}$, fruit length, number of fruit cluster$^{-1}$, and yield. ST-100 was found as a good general combiner for days to flowering. KHT-107 was found best for fruit width while KHT-103 for plant height. Hybrid T-1360 × ST-100 showed maximum specific combining ability (SCA) for yield (1.30 kg plant$^{-1}$), plant height (8.15 cm), number of fruit cluster$^{-1}$ (0.92), fruit length (0.57 cm), number of flowers cluster$^{-1}$ (0.70), and number of cluster plant$^{-1}$ (4.27). Hybrid ST-100 × KHT-107 showed maximum SCA for average fruit weight (14.85 g). Hybrid KHT-107 × KHT-103 displayed maximum SCA for fruit width (0.55 cm). Kumar *et al.* (2015a) also used the general and specific combining abilities in tomato hybrids for their evaluation.

**Variability analysis**

The estimation of GCA and SCA variances exhibited the existence of non-additive gene action for each measured trait. Observations revealed that the SCA variance was higher than the GCA variance (Table 5). GCA to SCA ratio was found below one, which confirmed the presence of non-additive gene action. Therefore, heterotic breeding is useful for the genetic improvement of such plant traits. Current outcomes are in line with the previous findings of Singh and Asati (2011) and Akram *et al.* (2019).

The high magnitude of the phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) were found for all the measured traits (Table 6). These high values show the presence of considerable variability, which confirmed the room for precision via selection (Sharma *et al.,* 2010). The results revealed a higher magnitude of PCV than the GCV value, although the difference between them was low, and it showed the existence of environmental factors in the ultimate expression of particular plant characteristics. Under such conditions, improvement in the crop plants can be performed through selection. Tembhurne *et al.* (2008) and Chattopadhyay *et al.* (2011) also

**Table 6.** Heritability and genetic advance for various traits in tomato.

| Traits | Grand Means | SeM | Range | | Variance | | | Coefficient of Variance | | | $h^2$ (%) | GA (%) Over Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Max. | Min. | Ve | Vg | Vp | ECV% | GCV% | PCV% | | |
| DF | 60.18 | 0.86 | 69.0 | 52.0 | 2.23 | 16.69 | 18.92 | 2.48 | 6.78 | 7.22 | 88 | 13.13 |
| DM | 110.93 | 1.21 | 120.0 | 101.0 | 4.35 | 17.08 | 21.44 | 1.88 | 3.72 | 4.17 | 79 | 6.85 |
| FC | 5.65 | 0.09 | 7.6 | 4.5 | 0.02 | 0.54 | 0.57 | 2.94 | 13.08 | 13.41 | 95 | 26.30 |
| FTC | 3.47 | 0.14 | 6.0 | 1.8 | 0.05 | 1.19 | 1.25 | 7.01 | 31.53 | 32.30 | 95 | 63.41 |
| CP | 26.64 | 1.11 | 38.0 | 18.0 | 3.72 | 25.70 | 29.42 | 7.23 | 19.02 | 20.35 | 87 | 36.63 |
| PH | 81.82 | 1.03 | 110.0 | 63.6 | 3.24 | 122.63 | 125.87 | 2.20 | 13.53 | 13.71 | 97 | 27.51 |
| AFW | 72.97 | 5.57 | 122.0 | 40.0 | 93.30 | 242.28 | 335.58 | 13.23 | 21.33 | 25.10 | 72 | 37.33 |
| FL | 6.56 | 0.14 | 8.0 | 4.8 | 0.06 | 0.53 | 0.60 | 3.83 | 11.15 | 11.79 | 89 | 21.72 |
| FW | 4.63 | 0.15 | 6.0 | 3.3 | 0.07 | 0.23 | 0.31 | 5.87 | 10.48 | 12.02 | 76 | 18.84 |
| Yield | 1.58 | 0.03 | 4.1 | 0.4 | 0.003 | 1.15 | 1.16 | 3.57 | 67.91 | 68.01 | 99 | 139.72 |

AFW = Average fruit weight (g), CP = Number of clusters per plant, DF = Days to 50% flowering, DM = Days to 50% maturity, FC = Number of flowers per cluster, FL = Fruit length (cm), FTC = Number of fruits per cluster, FW = Fruit width (cm), PH = Plant height (cm), Y = Yield (kg/plant), PCV = Phenotypic Coefficient of Variation, GCV = Genotypic Coefficient of Variation, ECV= Environmental Coefficient of Variation.

found the higher value of PCV over GCV in the *Solanaceae* family. Yanti (2016) also reported the higher magnitudes of GCV and PCV are indication of variability that can be used through selection for improvement in plant characteristics (number of fruits cluster$^{-1}$, fruit length, width, and weight) in the *Solanaceae* family.

**Heritability and genetic advance**

The high heritability in a broad sense varied from 72% to 92% among the measured traits (Table 6). The high genetic advance over the mean ranged from 36.63% to 139.72% for some of the recorded traits. The high magnitudes of heritability and genetic advance revealed the direction of selection, but the estimated heritability alone is not acceptable to study the response to selection. So, it is necessary to line up the values of heritability with genetic advances (Basavaraj *et al.,* 2010). The high magnitudes of heritability (72% to 92%) and genetic advance (36.63% to 139.72%) found for several cluster plant$^{-1}$, average fruit weight (g), number of fruits cluster$^{-1}$, and yield (kg plant$^{-1}$), showed a slight environmental effect on these traits, thus, improving these traits can be performed through selection (Figure 1). This also revealed the existence of additive gene action for such parameters (Elahi *et al.,* 2017a), and selection is a good technique for improving these traits based on their phenotypic behavior as confirmed by Elahi *et al.,* 2019b.

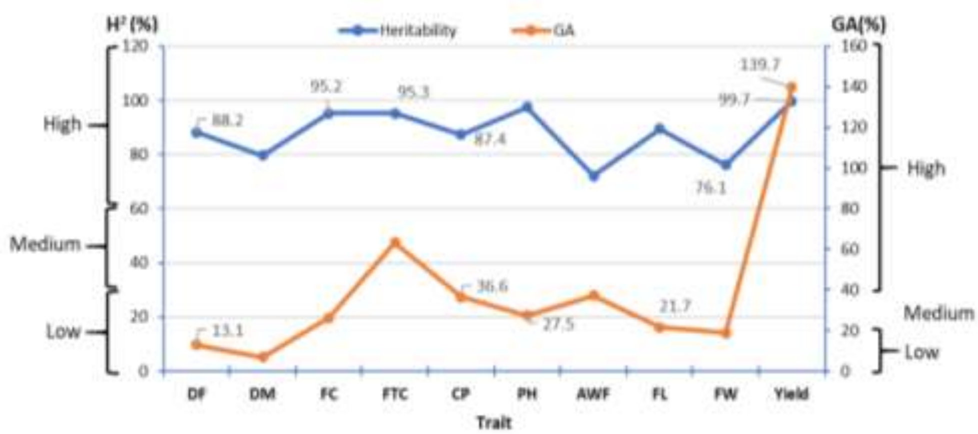


**Figure 1.** The trend of heritability and genetic advance in tomato hybrids along with parents. AFW = Average fruit weight (g), CP = Number of clusters per plant, DF = Days to 50% flowering, DM = Days to 50% maturity, FC = Number of flowers per cluster, FL = Fruit length (cm), FTC = Number of fruits per cluster, FW = Fruit width (cm), PH = Plant height (cm), Y = Yield (kg/plant).

**Heterotic studies**

The degree of heterosis regarding average fruit weight (g) ranged from 1.1% to 64% over the mid parents and 10.4% to 59.3% over the better parents (Table 7). Of the 12 hybrids, nine indicated positive heterosis over the mid parents and six hybrids disclosed positive heterosis over the better parents. Hybrid KHT-107 × ST-100 exhibited maximum mid parent (64) and better-parent (59.3) heterosis. Joshi and Thakur (2003) also found heterosis in hybrids' fruit weight. The heterosis for the number of cluster plant$^{-1}$ varied from 1.4% to 45.1% over the mid parents and 4.9% to 42.6% over the better parents. Of the 12 hybrids, seven hybrids exhibited positive heterosis over mid-parent heterosis and six hybrids disclosed positive heterosis over better-parent heterosis. ST-100 × T-1360 (45.1%) displayed maximum mid-parent heterosis and KHT-107 × ST-100 (42.6%) disclosed maximum better-parent heterosis. These findings are in line with the results of Garg and Cheema (2010). The degree of heterosis for days to 50% flowering varied from -14.0% to 8.4% over the mid parents and -18.3% to 5.3% over the better parents. A total of eight hybrids expressed negative heterosis over mid parents, whereas nine hybrids exhibited negative heterosis over the better parents. Hybrid ST-100 × KHT-103 exhibited early flowering by giving a high value of negative heterosis over the mid parents (-14.0%) and the better parents (-18.3%). Earliness in tomato hybrids was also described by Chauhan *et al.* (2014), as he reported early maturity in locally developed hybrids with enhanced fruit yield than parents. The magnitude of heterosis regarding days to 50% maturity ranged from -7.4% to 2.6% over the mid parents and -10.0% to 0.9% over the better parents. Only 10 hybrids exhibited negative heterosis over mid and better parents. ST-100 × KHT-103 (-7.4%) showed a high magnitude of negative mid-parent heterosis as compared with T-1360 × KHT-107 (-10.0%), which showed a high magnitude of negative better-parent heterosis. Kumar *et al.* (2012) and Javed *et al.* (2021) also testified to early maturity in hybrids.

The heterosis for the number of flower cluster$^{-1}$ diverged from 1.3% to 38.3% over the mid parents, and 6.1% to 28.8% over the better parents. Nine hybrids disclosed positive heterosis over the mid parents, whereas seven hybrids exhibited positive heterosis over the better parents. ST-100 × T-1360 expressed a high magnitude of heterosis over mid (38.0%) and better (28.8%) parents. The degree of heterosis for fruit length (cm) ranged from 2.7% to 23.2% over the mid parents while 5.9% to 22.7% over the better parents. Seven hybrids exhibited positive mid-parent heterosis, whereas only four hybrids indicated positive heterosis over the better parents. ST-100 × T-1360 exhibited maximum value of heterosis over the mid parents (23.2%) and the better parents (22.7%). Chattopadhyay and Paul (2012) also reported heterosis in fruit length in tomato hybrids, as they observed an increase in fruit length of developed hybrids than their parents. Regarding the number of fruits cluster$^{-1}$, the degree of heterosis ranged from 3.6% to 104.9% over the mid parents and 7.1% to 76.5% over the better parents.

All 12 hybrids showed positive heterosis over the mid parents while 11 hybrids showed positive heterosis over the better parents. T-1360 × KHT-103 disclosed maximum positive heterosis over the mid parents (104.9%), while ST-100 × T-1360 exhibited maximum positive heterosis over the better parents (76.5%). Gul *et al.* (2010) also reported heterosis for fruits cluster$^{-1}$ in different tomato hybrids. The magnitude of heterosis for fruit width (cm) varied from 1.6% to 36.5% over the mid parents and 0.6% to 24.2% over the better parents. Ten hybrids verified positive heterosis over the mid parents, while eight hybrids disclosed positive heterosis over the better parents. KHT-103 × KHT-107 showed a high scale of heterosis over the mid parents (36.5%) and the better parents (24.2%). These results are in line with the report of Dev *et al.* (1994) and Javed *et al.* (2021) regarding fruit width in different tomato hybrids. The heterosis regarding plant height (cm) over the mid parents varied from 2.0% to 19.7%, but over the better parents, heterosis on this trait varied from 10.1% to 13.6%. Four hybrids exhibited positive heterosis over the midparents and only two hybrids exhibited positive heterosis over the better parents. T-1360 × ST-100 exhibited a high magnitude of positive heterosis over the mid (19.7%) and better (13.6%) parents. The degree of heterosis regarding yield (kg plant$^{-1}$) ranged from 71.9% to 566.6% over the mid parents, while 54.2% to 455.5% over the better parents. Positive heterosis was observed for all hybrids over the mid parents, as well as, over the better parents. ST-100 × T-1360 exhibited maximum positive heterosis over the mid (566.6%) and better (455.5%) parents. Ahmad *et al.* (2011) also reported high magnitudes of heterosis regarding yield plant$^{-1}$ in different tomato hybrids.

**Table 7.** Heterotic performance of different tomato hybrids for various traits.

| P1 x P2 | AFW | | CP | | DF | | DM | | FC | | FL | | FTC | | FW | | PH | | Yield | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) | MPH (%) | BPH (%) |
| KHT-103 × KHT-107 | -29.0* | -39.6* | -13.5* | -24.7* | -2.8* | -5* | -0.1* | -1.9* | -5.3* | -11. 7 | -24.3 | -34.4 | 15.7* | 8.8* | 36.5* | 24.2* | -12.8 | -19.3 | 77.2* | 71.2* |
| KHT-103 × ST-100 | 32.8* | 10.4* | 19.7* | 4.9* | -1.9* | -6.8* | 2.2* | 0.9* | 20* | 16* | -5.0* | -14.5 | 68.0* | 43.9* | -2.5* | -15.0* | -11.3 | -26.4 | 281.3* | 245.8* |
| KHT-103 × T-1360 | -0.05* | -1.03* | -7.5* | -13.0* | -0.6* | -4.3* | -7.1 | -8.6 | 7.0* | -3.4* | -7.2* | -16.2 | 24.1* | 0* | 13.3* | 0.9* | 2.0* | -18.7 | 93.9* | 76.4* |
| KHT-107 × KHT-103 | -1.7* | -16.3* | -6.4* | -18.5* | -7.6* | -9.5 | -4.8* | -6.6 | -2.7* | -9.3* | -14.1 | -25.5 | 31.1* | 23.3* | 23.4* | 12.2* | -14.6 | -21.0 | 71.9* | 66.1* |
| KHT-107 × ST-100 | 64.0* | 59.3* | 43.8* | 42.6* | 7.3* | 4.2* | -1.1* | -1.7* | 15.4* | 11.1* | 14.3* | 9.6* | 72.4* | 56.1* | 12.3* | 6.9* | -16.7 | -25.9 | 350.5* | 321.8* |
| KHT-107 × T-1360 | 14.9* | -1.3* | -3.96* | -20. 7* | -3.8* | -5.4* | -3.8* | -7.1 | 1.3* | -2.2* | 5.8* | 1.1* | 8.3* | -8.3* | 23.8* | 20.8* | -1.6* | -16.5 | 120.5* | 94.4* |
| ST-100 × KHT-103 | 11.5* | -7.3* | 1.4* | -11.1* | -14.0* | -18.3 | -2.8* | -4.0* | 10.2* | 6.6* | -10.3* | -19.2 | 25* | 7.1* | 2.8* | -10.4* | -11.2 | -26.3 | 107.5* | 88.1* |
| ST-100 × KHT-107 | 55.2* | 50.8* | 35.5* | 34.4* | 8.4* | 5.2* | -7.4 | -8.0 | 10.2* | 6.1* | 10.4* | 5.9* | 36.8* | 23.9* | 5.6* | 0.6* | -17.6 | -26.8 | 162.1* | 145.5* |
| ST-100 × T-1360 | 69.6* | 42.2* | 45.1* | 20.6* | 2.9* | 1.6* | -2.1* | -4.9* | 38.3* | 28.8* | 23.2* | 22.7* | 90.1* | 76.5* | -11.7* | -13. 8* | 16.0* | 10.1* | 566.6* | 455.5* |
| T-1360 × KHT-103 | 33.9* | 32.6* | 19.1* | 11.9* | 3.4* | -0.5* | 2.6* | 0.9* | 27.4* | 15* | 7.5* | -2.9* | 104.9* | 65.1* | 9.9* | -2.2* | -2.2* | -22.1 | 419.0* | 372.2* |
| T-1360 × KHT-107 | 1.1* | -13.2* | -11.9* | -27.2 | -6.5* | -8.1* | -6.8 | -10 | -8.4* | -11.5 | 2.7* | -1.9* | 3.6* | -12.2* | 1.6* | -0.9* | 17.1* | -0.5* | 74.8* | 54.2* |
| T-1360 × ST-100 | 47.7* | 23.8* | 28.1* | 6.5* | -0.3* | -1.6* | -5.9 | -8.6 | 19.8* | 11.5* | 17.2* | 16.7* | 58.2* | 46.8* | 10.2* | 7.5* | 19.7* | 13.6* | 408.3* | 323.6* |

** Highly significant ($P \leq 0.01$), *Significant ($P \leq 0.05$), NS Non-significant ($P > 0.05$)
AFW = Average fruit weight (g), CP = Number of clusters per plant, DF = Days to 50% flowering, DM = Days to 50% maturity, FC = Number of flowers per cluster, FL = Fruit length (cm), FTC = Number of fruits per cluster, FW = Fruit width (cm), PH = Plant height (cm), Y = Yield (kg/plant)

## CONCLUSIONS

The study of the mode of inheritance of a particular trait gives a better assessment of the direction of selection. In the traits where additive gene action was recorded, selection in early generations will be effective. Dominance can be used well for heterosis breeding. Heterosis breeding is best for the improvement in yield and earliness. For earliness, days to 50% flowering and days to 50% maturity can play a vital role. However, for improvement in yield, the traits, i.e., the number of clusters plant$^{-1}$, the number of fruit cluster$^{-1}$, and average fruit weight, are highly considered. Among parents, T-1360 came in front as the best general combiner for yield. Hybrid T-1360 × ST-100 was found to be best overall among all the hybrids regarding fruit yield.


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