Plant Archives Vol. 25, Supplement 1, 2025 pp. 206-215 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-1.029

COMBINING ABILITY AND GENE ACTION STUDIES FOR YIELD AND ITS ATTRIBUTING TRAITS OVER DIFFERENT ENVIRONMENTS IN TOMATO (*SOLANUM LYCOPERSICUM* L.)

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(Date of Receiving : 04-07-2024; Date of Acceptance : 20-09-2024)

ABSTRACT

The development of high-yielding hybrids, varieties, genetic improvement, and optimal selection are key goals of an effective breeding program. Consequently, a study was carried out to evaluate the combining ability for yield and yield-contributing traits in tomato genotypes. The present research was undertaken to examine the combining ability of 11 parents and 28 hybrids that resulted from crossing of seven lines and four testers in line × tester mating design, for yield and quality governing traits in tomato over three different locations. Analysis of variance for combining ability revealed highly significant differences for mean square of SCA for all studied characters and GCA for fruit girth (cm). The ratio of σ^2GCA/σ^2SCA was lower than unity for fruit girth (cm) indicate the pre dominant role of non-additive gene action for inheritance. For fruits per plant and fruit yield per plant (kg), parents *viz*., DVRT-2 and GT-6 exhibited significant and positive GCA effects. In majority hybrids DVRT-2 and GT-6 reflects positive effects for getting higher yield. An analysis for the specific combining ability effect revealed that the hybrids *viz*., NTL-42 × DVRT-2, NTL-25 × AT-3, NTL-25 × DVRT-2, NTL-45 × GT-6 and NTL-19 × GT-6 was found positive and significant SCA effect for fruit yield per plant (kg) in all the three locations.

***Keywords*:** Combining ability, over the environments, GCA, SCA, Tomato

Introduction

Tomato (*Solanum lycopersicum* L., 2n = 24) ranks as the second most significant vegetable crop globally, following the potato, and leads among processed vegetables. Its origins are thought to be in tropical America, specifically the Peruvian and Mexican regions (Thompson and Kelly, 1957). In India, tomatoes were brought over by English traders from the East India Company in 1822 (Kalloo, 1988). This vegetable is part of the extensive Solanaceae family and is closely related to several important crops, including potatoes, eggplants, peppers, and tobacco. The tomato is a perennial herbaceous plant but is commonly grown as an annual in various ecological conditions, ranging from the high altitudes of the Himalayas to the plains of South India. It can be cultivated both in open fields and in polyhouses throughout the year. The most widely grown species, *Solanum lycopersicum* L., exhibits both determinate and indeterminate growth habits. The crop's cleistogamous flowers promote a high rate of self-pollination, though natural cross-pollination can occur up to 5 percent, primarily facilitated by insects (Salunkhe *et al*., 1987). Combining ability studies are highly valuable because they offer critical insights into the selection of parent plants based on hybrid performance and clarify the nature and extent of different gene actions involved in the expression of quantitative traits (Khoja and Ahmad, 2008). These analyses are powerful tools that estimate combining ability effects, helping in the selection of desirable parents and crosses for further development. Various methods exist for evaluating parent and cross combinations in terms of combining ability, with the Line × Tester approach (Kempthorne, 1957) being particularly effective for the preliminary assessment of genetic stocks. This method is instrumental in identifying strong combiners for use in hybridization programs.

Material and Methods

Experiment was carried out during Rabi 2021-22 at three different locations was carried out at three different locations *viz*., Vegetable Research Station, Regional Horticulture Research Station (R.H.R.S), NAU, Navsari (L1) (20.94°N, 72.95°E), Hill Millet Research Station, NAU, Waghai (L2), (20.77°N, 73.49°E) and Cotton Research Substation, NAU, Achhaliya (L3) (21.78°N, 73.27°E) situated in the region of south Gujarat. The experimental material consisted of 40 genotypes; representing 28 hybrids developed in line x tester mating of 7 lines, 4 testers (Seven lines *viz*., NTL-19, NTL-24, NTL-25, NTL-27, NTL-42, NTL-45, NTL-50 and four testers *viz*., Arka Anamika, DVRT-2, GT-6, GT-7 and AT-3) and check 'Arka Rakshak'. All the genotypes were evaluated in Randomized Block Design (RBD) replicated thrice in three environments. Observations were recorded on 14 characters *viz*., days to 50 % flowering, plant height (cm), branches per plant, fruits per plant, fruit yield per plant (kg), fruit weight (g), fruit length (cm), fruit girth (cm), pericarp thickness (mm), locules per fruit, total soluble solids (%), titrable acidity (mg/100g), ascorbic acid (mg/100g) and lycopene content (mg/100g). The data was analyzed using the Line x Tester method. Combining ability analysis was computed on the data obtained for parents and F_1s as per procedure reviewed by Singh and Chaudhary (1977), on the basis of design II of Comstock and Robinson (1952) and as further extended by Cockerham (1954, 1956) and Kempthrone (1957). This analysis was used for obtaining estimates of general and specific combining ability variances and effects.

Result and Discussion

The analysis of variance for combining ability, using lines x testers mating design in respect of 7 lines, 4 testers and twenty-eight hybrids for all the fourteen characters in individual location and pooled over locations (pooled basis) is presented in Table 1.

The mean sum of squares was partitioned into various parts *viz.,* mean squares due to replication, lines, testers, line × testers and error at individual location as well as pooled analysis while, it was divided into environments, line × environments, testers × environments, line × testers × environments and pooled error at pooled analysis.

Variance due to female (lines) was significant for fruit girth (cm) and pericarp thickness (mm), variance due to male (testers) was significant for plant height (cm) at Navsari (L1) and Waghai (L2), fruits per plant and fruit yield per plant (kg) and fruit girth (cm) at all location, locules per fruit at Navsari (L1) and ascorbic acid (mg/100g) at Navsari (L1). Variance due to female × male interaction was found significant for all characters at all locations. This indicated significant contribution of lines × testers which reflect more importance of specific combining ability variance component for most of the traits. Similar result was reported by Dharva *et al.* (2018), Mishra *et al.* (2020), Kumar *et al.* (2020), Izzo *et al.* (2022), Lone *et al.* (2022) and Reddy *et al.* (2023).

σ^2SCA were significant for all the characters in all the three locations. Significant SCA effect indicates that the hybrids are somewhere different from the parents involved in every given hybrid. Similar outcome was also noticed for days to 50% flowering by Dharva *et al.* (2018), Mishra *et al.* (2020) and Izzo *et al*. (2022); for plant height (cm) by Farwah *et al.* (2022), Bhajantri *et al.* (2021)¸ Lone *et al.* (2022) and Farwah *et al.* (2022); for branches per plant Mishra *et al.* (2020), Lone *et al.* (2022) and Farwah *et al.* (2022); for fruits per plant by Vekariya *et al.* (2019), Huseynzade *et al.* (2020) and Lone *et al.* (2022); for fruit yield per plant (kg) by Izzo *et al*. (2022), Lone *et al.* (2022) and Madhavi *et al.* (2023); for fruit weight (g) by Bhajantri *et al.* (2021), Izzo *et al.* (2022) and Lone *et al.* (2022); for fruit length (cm) and fruit girth (cm) by Izzo *et al.* (2022), Lone *et al.* (2022) and Reddy *et al*. (2023); for pericarp thickness (mm) by Bhajantri *et al*. (2021), Kumar and Singh (2022) and Lone *et al*. (2022); for locules per fruit by Bhajantri *et al*. (2021), Izzo *et al*. (2022) and Lone *et al.* (2022); for total soluble solids (%) by Bhajantri *et al.* (2021), Kumar and Singh (2022) and Sankhala *et al.* (2022); for titrable acidity (mg/100g) by Dharva *et al.* (2018) and Kumar and Singh (2022); for ascorbic acid (mg/100g) by Kumar *et al.* (2020) and Kumar and Singh (2022); for lycopene content (mg/100g) by Farwah *et al.* (2022), Kumar *et al*. (2020) and Sankhala *et al.* (2022).

Both σ^2GCA and σ^2SCA variance were significant for fruit girth (cm). It indicates that both additive and non-additive components of gene actions are involved in the expression of those characters. The relative magnitude of these variance indicated that non additive gene effect was more prominent for these characters. Similar result was recorded by Dharva *et al.* (2018), Mishra *et al.* (2020), Kumar *et al*. (2020), Izzo *et al.* (2022), Lone *et al*. (2022) and Reddy *et al.* (2023).

σ^2GCA/ σ^2SCA ratio less than unity for fruit girth (cm) showing the influence of non-additive gene action. Hence, heterosis breeding and recombination breeding with postponement of selection at later generations are ideal for improvement of fruit girth (cm). Similar result was observed by Kumar *et al.* (2020), Izzo *et al.* (2022), Lone *et al*. (2022) and Reddy *et al.* (2023).

Estimation of general combining ability effect

General combining ability effects of females (lines) for fruit girth (cm) and pericarp thickness (mm) and general combining ability effects of males (testers) for plant height (cm), fruits per plant, fruit yield per plant (kg), fruit girth (cm) and ascorbic acid (mg/100g) were estimated. Estimates of general combining ability and specific combining ability effects are calculated when mean square for GCA and SCA are significant. Several times GCA and SCA effects are calculated, through the mean squares for these components are non-significant. It is meaningless, non-significant of mean squares for GCA and SCA suggests that there are non-significant differences among the GCA effects of parents and SCA effects of cross combinations. Hence, in this experiment we are calculated the gene action on the basis of significant GCA and SCA mean square as well as variance. We didn't consider the values of GCA and SCA effects which are non-significant mean square in ANOVA.

Plant height (cm)

The GCA effect of testers ranged from -10.80 (AT-3) to 13.29 (GT-6) at Navsari (L1), -12.29 (AT-3) to 13.53 (GT-6) at Waghai (L2). Among testers, GT-6 and GT-7 at Navsari (L1) (13.29 and 2.11) and Waghai (L2) (13.53 and 2.84) possessed positive and significant GCA effect. Similar result were observed by Sharma and Sharma (2010) and Huseynzade *et al.* (2020).

Fruits per plant

Among parents, the range of GCA effect for testers was varied between -6.64 (GT-7) to 7.10 (DVRT-2) at Navsari (L1), -5.60 (GT-7) to 6.64 (DVRT-2) at Waghai (L2), -5.86 (GT-7) to 7.32 (DVRT-2) at Achhaiya (L3). Among testers, DVRT-2 (7.10) and GT-6 (4.38) at Navsari (L1), DVRT-2 (6.63) and GT-6 (2.40) at Waghai (L2) and DVRT-2 (7.32) and GT-6 (2.51) at Achhaliya (L3) possessed positive and significant GCA effect. Similar result was recorded by Barragán *et al.* (2019) and Bhajantri *et al.* (2021).

Fruits yield per plant (kg)

The GCA effects of testers ranged for this trait from -0.55 (GT-7) to 0.40 (DVRT-2) at Navsari (L1); -0.56 (GT-7) to 0.37 (DVRT-2) at Waghai (L2) and -0.56 (GT-7) to 0.41 (DVRT-2) at Achhaliya (L3). Among testers, DVRT-2 (0.40) and GT-6 (0.33) at Navsari (L1), DVRT-2 (0.37) and GT-6 (0.26) at Waghai (L2) and DVRT-2 (0.41) and GT-6 (0.33) at Achhaliya (L3) possessed positive and significant GCA effect. Similar result was observed by Kumar *et al*. (2015).

Fruit girth (cm)

The range of GCA effect among lines was found from -4.00 (NTL-50) to 0.29 (NTL-24) at Navsari (L1), -0.66 (NTL-50) to 0.45 (NTL-19) at Waghai (L2) and -0.59 (NTL-50) to 0.36 (NTL-19) at Achhaliya (L3). NTL-24 (0.29), NTL-19 (0.21), NTL-27 (0.14), NTL-25 (0.09) and NTL-42 (0.06) at Navsari (L1); NTL-24 (0.15), NTL-19 (0.45), NTL-27 (0.22) and NTL-42 (0.06) at Waghai (L2) and NTL-24 (0.31), NTL-19 (0.36), NTL-27 (0.17) and NTL-42 (0.09) at Achhaliya (L3) possessed positive and significant GCA effect. Similar result was observed by Dagade *et al.* (2015), Barragán *et al.* (2019) and Huseynzade *et al.* (2020).

Among testers range of GCA effect found from -4.00 (GT-7) to 0.34 (DVRT-2) at Navsari (L1), -0.30 (GT-7) to 0.39 (DVRT-2) at Waghai (L2) and -0.29 (GT-7) to 0.39 (DVRT-2) at Achhaliya (L3). DVRT-2 (0.34) and GT-6 (0.17) at Navsari (L1) and DVRT-2 at Waghai (L2) (0.39) and Achhaliya (L3) (0.39) possessed positive and significant GCA effect. Similar result was observed by Mishra *et al.* (2020), Kumar *et al.* (2020) and Izzo *et al.* (2022).

Pericarp thickness (mm)

The GCA effects of lines ranged for this trait from -0.52 (NTL-45) to 0.74 (NTL-19) at Navsari (L1); -0.57 (NTL-45) to 0.87 (NTL-19) at Waghai (L2) and -0.53 (NTL-45) to 0.66 (NTL-19) at Achhaliya (L3). Among lines, NTL-19 (0.74) and NTL-42 (0.35) at Navsari (L1), NTL-19 (0.87) and NTL-42 (0.34) at Waghai (L2) and NTL-19 (0.66), NTL-24 (0.16) and NTL-42 (0.36) at Achhaliya (L3) possessed positive and significant GCA effect. Similar results were observed by Aisyah *et al*. (2016), Huseynzade *et al*. (2020) and Kumar *et al*. (2020).

Ascorbic acid (mg/100g)

Among testers, the range of GCA effect was varied between -1.26 (GT-7) to 0.67 (GT-6) at Navsari (L1). Positive and significant GCA effect were possessed by DVRT-2 (0.67) and GT-6 (0.42). Similar result was reported by Kumar *et al.* (2020) and Kumar and Singh (2022).

Estimation of specific combining ability effect

The SCA effects of crosses were significant for all characters. The salient features of SCA effects of hybrids in different traits estimated are given as below:

Days to 50 % flowering

Range of SCA effect among the hybrids varied from -4.10 (NTL-24 × AT-3) to 4.47 (NTL-45 × GT-6) at Navsari (L1), -5.36 (NTL-45 × GT-6) to 5.54 (NTL-19 × GT-6) at Waghai (L2) and -4.84 (NTL-24 × AT-3) to 5.76 (NTL-42 × DVRT-2) at Achhaliya (L3).

Negative and significant SCA effects were found in top three hybrids *viz.,* NTL-24 × AT-3 (-4.10), NTL-45 × GT-7 (-2.85) and NTL-50 × DVRT-2 (-2.51) at Navsari (L1); NTL-45 × GT-7 (-5.36), NTL-19 × GT-6 (-3.16) and NTL-19 × AT-3 (-2.69) at Waghai (L2) and NTL-24 × AT-3 (-4.85), NTL-25 × GT-7 (-4.25) and NTL-42 × GT-6 (-3.66) at Achhaliya (L3), respectively. Hybrid NTL-24 × AT-3 had negative and significant SCA effects for all location.

Ahmad *et al.* (2009), Dharva *et al.* (2018), Kumar *et al.* (2020), Mishra *et al.* (2020) and Izzo *et al.* (2022) also reported similar kind of results for this trait.

Plant height (cm)

The range of SCA effect for plant height (cm) from -11.20 (NTL-24 × GT-7) to 13.43 (NTL-24 × GT-6) at Navsari (L1); -14.07 (NTL-19 × AT-3) to 11.68 (NTL-42 × GT-7) at Waghai (L2) and -14.33 (NTL-24 × GT-7) to 11.49 (NTL-19 × GT-7) at Achhaliya (L3). The outstanding hybrid with positive and significant SCA effect were NTL-24 × GT-6 (13.43), NTL-42 × GT-7 (10.75) and NTL-45 × AT-3 (7.04) at Navsari (L1); NTL-42 × GT-7 (11.68), NTL-24 × GT-6 (10.03) and NTL-27 × DVRT-2 (9.20) at Waghai (L2) and NTL-24 × GT-7 (11.71), NTL-19 × GT-6 (7.17) and NTL-25 × DVRT-2 (5.30) at Achhaliya (L3).

These finding were in line with the earlier reports of Farwah *et al.* (2022), Bhajantri *et al.* (2021), Lone *et al.* (2022) and Farwah *et al.* (2022).

Branches per plant

The ranged for SCA effect for branches per plant from -1.80 (NTL-45 × DVRT-2) to 3.21 (NTL-42 × DVRT-2) at Navsari (L1); -1.67 (NTL-42 × GT-7) to 2.65 (NTL-45 × GT-6) at Waghai (L2) and -1.65 (NTL-42 × GT-7) to 2.66 (NTL-42 × DVRT-2) at Achhaliya (L3).The top three hybrids *viz.,* NTL-42 × DVRT-2 (3.21) followed by NTL-45 × GT-6 (3.14) and NTL-25 × DVRT-2 (1.82) at Navsari (L1); NTL-45 × GT-6 (2.65) followed by NTL-42 × DVRT-2 (2.53) and NTL-25 × DVRT-2 (1.71) at Waghai (L2) and NTL-42 × DVRT-2 (2.66) followed by NTL-45 × GT-6 (1.86) and (NTL-50 × AT-3 (1.75) at Achhaliya (L3) had found higher significant and positive SCA effect.

Vekariya *et al.* (2019), Mishra *et al.* (2020), Lone *et al.* (2022) and Farwah *et al.* (2022) also reported similar kind of results for this trait.

Fruits per plant

The estimates of SCA effects in hybrids ranged from -7.24 (NTL-24 × DVRT-2) to 9.19 (NTL-25 × AT-3) at Navsari (L1); -6.52 (NTL-25 × GT-7) to 9.77 (NTL-25 × AT-3) at Waghai (L2) and -14.74 (NTL-24 × DVRT-2) to 11.71 (NTL-24 × GT-7) at Achhaliya (L3) for fruits per plant.

Among the hybrids, highest positive and significant SCA effect were possessed by hybrids *viz.,* NTL-25 × AT-3 (9.19), NTL-42 × DVRT-2 (8.66) and NTL-45 × GT-6 (7.75) at Navsari (L1); NTL-25 × AT-3 (9.77), NTL-42 × DVRT-2 (7.40) and NTL-24 × GT-7 (6.20) at Waghai (L2) and NTL-24 × GT-7 (11.71), NTL-19 × GT-6 (7.17) and NTL-25 × DVRT-2 (5.30) at Achhaliya (L3). Similar result were observed by Bhalala and Acharya (2019), Vekariya *et al.* (2019), Huseynzade *et al.* (2020) and Lone *et al.* (2022).

Fruit yield per plant

The estimates of SCA effects in hybrids varied from -0.97 (NTL-24 × DVRT-2) to 0.90 (NTL-42 × DVRT-2); -1.09 (NTL-24 × DVRT-2) to 0.78 (NTL-42 × DVRT-2) and -0.82 (NTL-24 × DVRT-2) to 0.88 (NTL-25 × AT-3) at Navsari (L1), Waghai (L2), Bardoli (L3), respectively.

Significant and positive SCA effects for higher fruit yield per plant (kg) were observed for three hybrids *viz.,* NTL-42 × DVRT-2 (0.90), NTL-25 × AT-3 (0.81) and NTL-24 × GT-3 (0.70) at Navsari (L1). In addition, two hybrids *viz.,* NTL-42 × DVRT-2 (0.78) and NTL-24 × GT-7 (0.74) and NTL-25 × AT-3 (0.68) at Waghai (L2) and NTL-25 × AT-3 (0.88), NTL-42 × DVRT-2 (0.85) and NTL-24 × GT-7 (0.66) at Achhaliya (L3) had positive and significant SCA effect.

Similar finding in accordance to the above result has also been reported by Kumar *et al.* (2020), Bhajantri *et al*. (2021), Izzo *et al*. (2022), Lone *et al.* (2022) and Madhavi *et al.* (2023).

Fruit weight (g)

The estimates of SCA effects in hybrids for fruit weight (g) varied from -0.97 (NTL-24 × DVRT-2) to 0.90 (NTL-42 × DVRT-2); -1.09 (NTL-24 × DVRT-2) to 0.78 (NTL-42 × DVRT-2) and -0.82 (NTL-24 × DVRT-2) to 0.88 (NTL-25 × AT-3) at Navsari (L1), Waghai (L2), Achhaliya (L3), respectively.

Among hybrids, NTL-25 × DVRT-2 (8.80), NTL-42 × DVRT-2 (6.43) and NTL-19 × GT-6 (5.64) at Navsari (L1), NTL-25 × DVRT-2 (8.98), NTL-42 × GT-7 (7.34) and NTL-19 × GT-6 (5.77) at Waghai (L2), NTL-42 × GT-7 (9.42), NTL-25 × DVRT-2 (7.90) and NTL-27 × GT-6 (6.74) at Achhaliya (L3) exhibited significant and desirable SCA effects. Conformity results were reported by Bhalala and Acharya (2019), Vekariya *et al*. (2019), Kumar *et al.* (2020), Bhajantri *et al* (2021) and Lone *et al*. (2022).

Fruit length (cm)

The range of hybrid for fruit length (cm) was -4.88 (NTL-50 × GT-6) to 0.46 (NTL-45 × GT-6); -0.46 (NTL-50 × GT-6) to 0.44 (NTL-45 × GT-6) and -0.49 (NTL-25 × GT-7) to 0.46 (NTL-42 × GT-7) at Navsari (L1), Waghai (L2), Achhaliya (L3), respectively.

The hybrids *viz.,* NTL-45 × GT-6 (0.46), NTL-42 × GT-7 (0.42) and NTL-24 × AT-3 (0.34) at Navsari (L1), NTL-45 × GT-6 (0.44), NTL-24 × AT-3 (0.38) and NTL-42 × GT-7 (0.35) at Waghai (L2), NTL-42 × GT-7 (0.46), NTL-45 × GT-6 (0.35) and NTL-24 × AT-3 (0.31) at Achhaliya (L3) exhibited positive and significant SCA effect at all the locations, which showed they were good specific combiner for this trait. Kumar *et al*. (2020), Izzo *et al.* (2022), Lone *et al.* (2022) and Reddy *et al*. (2023) were also observed same results.

Fruit girth (cm)

The range of hybrid for fruit girth (cm) was -0.62 (NTL-19 × AT-3) to 0.64 (NTL-25 × AT-3); -0.68 (NTL-42 × DVRT-2) to 0.71 (NTL-45 × DVRT-2) and -0.74 (NTL-42 × DVRT-2) to 0.84 (NTL-45 × DVRT-2) at Navsari (L1), Waghai (L2), Achhaliya (L3), respectively.

Among hybrids, NTL-25 × AT-3 (0.64), NTL-45 × GT-6 (0.52) and NTL-24 × GT-7 (0.24) at Navsari (L1), NTL-45 × DVRT-2 (0.71), NTL-42 × GT-7 (0.70) and NTL-25 × AT-3 (0.32) at Waghai (L2), NTL-45 × DVRT-2 (0.84), NTL-42 × GT-7 (0.77) and NTL-24 × GT-7 (0.37) at Achhaliya (L3) exhibited significant and desirable SCA effects. Conformity results were reported by Mishra *et al.* (2020), Kumar *et al*. (2020), Izzo *et al*. (2022), Lone *et al*. (2022) and Reddy *et al.* (2023).

Pericarp thickness (mm)

The estimates of SCA effects in hybrids varied from -0.57 (NTL-19 ×GT-6) to 0.98 (NTL-24 × GT-6); -0.66 (NTL-19 ×GT-6) to 1.04 (NTL-24 × GT-6) and -0.49 (NTL-19 ×GT-6) to 0.88 (NTL-24 × GT-6) at Navsari (L1), Waghai (L2), Achhaliya (L3), respectively.

Among hybrids, NTL-24 × GT-6 (0.98), NTL-19 × AT-3 (0.84) and NTL-50 × DVRT-2 (0.54) at Navsari (L1), NTL-24 × GT-6 (1.04), NTL-19 × AT-3 (0.88) and NTL-50 × DVRT-2 (0.61) at Waghai (L2), NTL-24 × GT-6 (0.88), NTL-19 × AT-3 (0.77) and NTL-42 × GT-7 (0.44) at Achhaliya (L3) exhibited significant and desirable SCA effects. Conformity results were reported by Dagade *et al*. (2015), Kumar *et al*. (2020), Mishra *et al.* (2020), Bhajantri *et al*. (2021) and Lone *et al*. (2022).

Locules per fruit

The range of SCA effect among hybrids for locules per fruit was varied from -0.82 (NTL-25 × GT-7) to 1.27 (NTL-45 × DVRT-2) at Navsari (L1), -0.98 (NTL-42 × DVRT-2) to 1.38 (NTL-25 × GT-7) at Waghai (L2) and -1.02 (NTL-42 × DVRT-2) to 1.47 (NTL-45 × DVRT-2) at Achhaliya (L3).

Among hybrids, NTL-25 × GT-6 (-0.82), NTL-42 × DVRT-2 (-0.77) and NTL-45 × GT-7 (-0.68) at Navsari (L1), NTL-42 × DVRT-2 (-0.98), NTL-25 × AT-3 (-0.71) and NTL-45 × GT-7 (-0.64) at Waghai (L2), NTL-42 × DVRT-2 (-1.02), NTL-27 × DVRT-2 (-0.63) and NTL-45 × GT-7 (-0.61) at Achhaliya (L3) exhibited significant and desirable SCA effects. Conformity results were reported by Bhalala and Acharya (2019), Bhajantri *et al*. (2021), Izzo *et al*. (2022), Lone *et al.* (2022) and Sankhala *et al.* (2022).

Total soluble solids (%)

The estimates of SCA effects in hybrids for total soluble solids varied from -0.58 (NTL-45 × DVRT-2) to 0.30 (NTL-50 × DVRT-2); -0.57 (NTL-45 × DVRT-2) to 0.85 (NTL-19 × AT-3) and -0.30 (NTL-19 × GT-7) to 0.40 (N, TL-50 × DVRT-2) at Navsari (L1), Waghai (L2), Achhaliya (L3), respectively.

Among hybrids, NTL-50 × DVRT-2 (0.30), NTL-45 × AT-3 (0.24) and NTL-19 × GT-6 (0.22) at Navsari (L1), NTL-19 × AT-3 (0.85), NTL-45 × GT-7 (0.35) and NTL-50 × DVRT-2 (0.35) at Waghai (L2), NTL-50 × DVRT-2 (0.40), NTL-45 × AT-3 (0.32) and NTL-42 × DVRT-2 (0.31) at Achhaliya (L3) exhibited significant and desirable SCA effects. Conformity results were reported by Dharva *et al.* (2018), Vekariya *et al.* (2019), Kumar *et al.* (2020), Bhajantri *et al.* (2021), Kumar and Singh (2022) and Sankhala *et al.* (2022).

Titrable acidity (mg/100g)

The estimates of SCA effects in hybrids for titrable acidity (mg/100g) varied from -0.11 (NTL-24 × GT-7) to 0.14 (NTL-27 × GT-7); -0.11 (NTL-24 × GT-7) to 0.14 (NTL-27 × GT-7) and -0.11 (NTL-24 × GT-7) to 0.09 (NTL-45 × GT-7) at Navsari (L1), Waghai (L2), Achhaliya (L3), respectively.

Among hybrids, NTL-27 × GT-7 (0.14), NTL-50 × GT-6 (0.07) and NTL-45 × GT-7 (0.05) at Navsari (L1), NTL-27 × GT-7 (0.14), NTL-42 × AT-3 (0.08) and NTL-45 × GT-6 (0.06) at Waghai (L2), NTL-45 × GT-7 (0.09), NTL-27 × GT-7 (0.06) and NTL-25 × GT-6 (0.05) at Achhaliya (L3) exhibited significant and desirable SCA effects. Conformity results were reported by Dharva *et al.* (2018) and Kumar and Singh (2022).

Ascorbic acid (mg/100g)

The spectrum of variation for SCA effects in hybrids for ascorbic acid (mg/100g) range from -1.52 (NTL-27 × GT-7) to 1.68 (NTL-50 × GT-6); -3.58 (NTL-24 × GT-6) to 3.34 (NTL-24 × GT-7) and -3.59 (NTL-25 × DVRT-2) to 3.49 (NTL-25 × AT-3) at Navsari (L1), Waghai (L2) and Achhaliya (L3).

Among these, hybrids *viz.,* NTL-50 × GT-6 (1.68), NTL-27 × DVRT-2 (1.66) and NTL-25 × AT-3 (1.32) at Navsari (L1), NTL-24 × GT-7 (3.34), NTL-45 × GT-6 (2.01) and NTL-25 × GT-6 (1.84) at Waghai (L2), NTL-25 × AT-3 (3.49), NTL-27 × DVRT-2 (2.74) and NTL-42 × GT-6 (2.60) at Achhaliya (L3) exhibited significant and desirable SCA effects. Similar results were reported by Kumar *et al.* (2020) and Kumar and Singh (2022).

Lycopene content (mg/100g)

The range of variation for SCA effects in hybrids for lycopene content (mg/100g) ranged from -0.03 (NTL-42 × GT-7) to 0.02 (NTL-45 × GT-7); -0.03 (NTL-45 × AT-3) to 0.02 (NTL-45 × GT-7) and -0.02 (NTL-42 × GT-6) to 0.02 (NTL-42 × AT-3) at Navsari (L1), Waghai (L2) and Achhaliya (L3).

Among hybrids, NTL-45 × GT-7 (0.024), NTL-42 × AT-3 (0.023) and NTL-42 × DVRT-2 (0.020) at Navsari (L1), NTL-45 × GT-7 (0.023), NTL-42 × AT-3 (0.022) and NTL-25 × AT-3 (0.017) at Waghai (L2), NTL-42 × AT-3 (0.029), NTL-42 × DVRT-2 (0.028) and NTL-45 × GT-7 (0.025) at Achhaliya (L3) exhibited significant and desirable SCA effects. Similar results were reported by Bhalala and Acharya (2019), Farwah *et al.* (2022) and Sankhala *et al.* (2022).

The current analysis revealed that none of the parents were good general combiners for all of the characteristics and these results were also reported earlier by Huseynzade *et al.* (2020), Mishra *et al.* (2020), Kumar *et al.* (2020) and Izzo *et al.* (2022).

Among the parents, DVRT-2 was found good general combiner for fruits per plant, fruit yield per plant (kg), fruit girth (cm) at all location and ascorbic acid (mg/100g) at Navsari (L1); GT-6 for plant height (cm) at Navsari (L1) and Waghai (L2), for fruits per plant at Waghai (L2) and Achhaliya (L3), for fruit yield per plant (kg) at all locations and for fruit girth (cm), and ascorbic acid (mg/100g) at Navsari (L1); GT-7 for plant height (cm) at Navsari (L1) and Waghai (L2); NTL-19 and NTL-42 for fruit girth (cm) at all location, for pericarp thickness (mm)at Waghai (L2) and Achhaliya (L3); NTL-24 and NTL-27 for fruit girth (cm) at all locations and NTL-25 for fruit girth (cm) at Navsari (L1) which possessed significant GCA effects in desired direction.

Among the hybrids, specific combing ability was significant in desirable direction for all the characters in one or more locations. Significant specific combing ability (SCA) in favourable direction was observed in many hybrids for days to 50 % flowering (4), for plant height (cm) (9), for branches per plant (10), for fruits per plant (6), for fruit yield per plant (kg) (9), for fruit weight (g) (12), for fruit length (cm) (3), for fruit girth (cm) (13), for pericarp thickness (mm) (5), for locules per fruit (10), for total soluble solids (15), for titrable acidity (mg/100g) (7), for ascorbic acid (mg/100 g) (5)and lycopene content (mg/100g) (7) at Navsari (L1); for days to 50 % flowering (9), for plant height (cm) (9), for branches per plant (11), for fruits per plant (6), for fruit yield per plant (kg) (8), for fruit weight (g) (14), for fruit length (cm) (3), for fruit girth (cm) (10), for pericarp thickness (mm) (4), for locules per fruit (9), for total soluble solids (12), for titrable acidity (mg/100g) (12), for ascorbic acid (mg/100 g) (7) and lycopene content (mg/100g) (5) at Waghai (L2) and for days to 50 % flowering (10), for plant height (cm) (10), for branches per plant (9), for fruits per plant (9), for fruit yield per plant (kg) (8), for fruit weight (g) (11), for fruit length (cm) (3), for fruit girth (cm) (9), for pericarp thickness (mm) (6), for locules per fruit (9), for total soluble solids (%) (12), for titrable acidity (mg/100g) (11), for ascorbic acid (mg/100 g) (5) and lycopene content (mg/100g) (9) at Achhaliya (L3).

In present study, mean sum of square for SCA were significant for all characters at all three locations. Mean sum of square for GCA and SCA were significant for fruit girth (cm) for all location indicate non-additive effect for trait. Similar results were observed by Dharva *et al*. (2018), Izzo *et al*. (2022), Lone *et al*. (2022) and Reddy *et al*. (2023).

The crosses showing low SCA effects may exhibited high per se performance *viz*., NTL-50 × DVRT-2 at Navsari (L1); NTL-50 × GT-6 and NTL-50 × DVRT-2 at Waghai (L2) and Achhaliya (L3).Similar results was observed by Kumar *et al*.(2020) and Bhajantri et al. (2021). The hybrid NTL-19 × GT-6, NTL-25 × DVRT-2, NTL-25 × AT-3, NTL-42 × DVRT-2 and NTL-45 × GT-6 exhibited high heterosis coupled with high SCA effects for fruit yield (table 4.33 to table 4.35). The ranking of crosses based on SCA effects and per se performance of hybrids differ in top yielding hybrids. Similar results were observed by Dagade *et al*. (2015), Dharva *et al.* (2018), Bhalala and Acharaya (2019), Lone *et al.* (2022) and Madhavi *et al*. (2023).

A comparison of the crosses selected on the basis of their SCA effects with their mean performance revealed some important features 1) the relative ranking of the various crosses on the basis of SCA effects was different in different environments 2) crosses showing high mean performance had not always shown high SCA effects. There was no consistent association between the *per se* performance of hybrid and their SCA effects. Similar results have been reported by Huseynzade *et al*. (2020), Mishra *et al*. (2020), Kumar *et al*. (2020) and Izzo *et al*. (2022). The choice of the best cross combinations on the basis of *per se* performance could be more realistic and useful. Almost identical results have been reported by Vekariya *et al*. (2019), Kumar *et al*. (2020) and Lone *et al*. (2022).

Conclusion

Analysis of variance for combining ability revealed highly significant differences for mean square of line × testers for all studied characters indicating that non additive gene effect was important for inheritance of these characters. The ratio of σ^2GCA/σ^2SCA was lower than unity for the fruit girth (cm) indicate the pre dominant role of non-additive gene action for inheritance of this traits. So, hybridization followed by selection were practiced for improvement of the fruit girth (cm). An analysis for the general combining ability effect revealed that DVRT-2 and GT-6 was found positive and significant GCA effect for fruit per plant and fruit yield per plant (kg) in all three locations.An analysis for the specific combining ability effect revealed that the hybrids *viz*., NTL-42 × DVRT-2, NTL-25 × AT-3, NTL-25 × DVRT-2, NTL-45 × GT-6 and NTL-19 × GT-6 was found positive and significant SCA effect for fruit yield per plant (kg) in all the three locations.

Acknowledgement

The authors acknowledge the support given by Department of Genetics and Plant Breeding, N. M. College of Agriculture Navsari Agricultural University, Navsari, Gujarat. We are also grateful to the group of vegetable scientists of Department of Vegetable Science, Navsari Agricultural University, Navsari, Gujarat, India.

Table 1: Analysis of variance for combining ability for all characters at individual location and pooled (P) over locations

Source of variation	df	Days to 50% flowering				Plant height (cm)				Branches per plant				Fruits per plant				Fruit yield per plant (kg)				Fruit weight (g)				Fruit length (cm)			
		L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P
Replications (R)	2	0.25	1.58	6.65	3.65	12.10	16.16	1.53	24.06	0.01	0.03	0.05	0.001	4.28	4.96	34.72	1.35	0.02	0.02	0.05	0.06	1.52	1.07	5.30	2.54	**0.12**	**0.12**	**0.08**	**0.32**
Lines (L)	6	21.9	19.3	15.9	36.18	455.4	371.68	174.20	921.53	2.81	3.49	5.75	10.69	96.14	129.62	61.94	221.88	0.78	0.53	0.77	2.00	90.47	142.91	157.13	369.49	**0.28**	**0.35**	**0.51**	**1.08**
Testers (T)	3	2.60	5.30	24.0	14.97	2232**	2513.51**	388.01	4467.99**	20.43	9.13	8.88	36.45	961.52**	652.09**	771.24**	2354.59**	4.35**	3.70*	4.39*	12.37*	100.422	100.18	102.50	292.77	**0.006**	**0.008**	**0.02**	**0.03**
Lines × Testers	18	17.01**	26.68**	47.56**	56.11**	180.5**	229.81**	256.68**	508.48**	8.26**	6.79**	6.73**	20.56**	92.30**	77.32**	136.22**	253.34**	1.03**	0.96**	0.89**	2.85**	96.56**	83.97**	108.05**	252.61**	**0.26****	**0.24****	**0.30****	**0.77****
Environments (E)	2	-	-	-	30.36**	-	-	-	30.65*	-	-	-	12.64**	-	-	-	460.7**	-	-	-	0.66**	-	-	-	220.1**	-	-	-	**0.41***
Lines × Envt.	12	-	-	-	10.54	-	-	-	39.90	-	-	-	0.68	-	-	-	32.91	-	-	-	0.04	-	-	-	10.51	-	-	-	**0.03**
Testers × Envt.	6	-	-	-	8.48	-	-	-	333.24**	-	-	-	1.00	-	-	-	15.13	-	-	-	0.04	-	-	-	5.17	-	-	-	**0.002**
Line × Testers × E	36	-	-	-	17.57**	-	-	-	79.27**	-	-	-	0.61**	-	-	-	26.25**	-	-	-	0.03	-	-	-	17.98**	-	-	-	**0.02**
Error	54	3.10	0.81	2.02	-	15.71	9.87	1.79	-	0.04	0.03	0.08	-	10.96	6.02	10.21	-	0.04	0.04	0.03	-	2.27	0.84	4.022	-	**0.05**	**0.05**	**0.04**	-
Pooled Error	162	-	-	-	1.98	-	-	-	9.12	-	-	-	0.05	-	-	-	9.06	-	-	-	0.04	-	-	-	2.38	-	-	-	**0.05**
σ^2GCA		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
σ^2SCA		4.66**	8.6**	15.10**	6.01**	56.05**	74.09**	84.86**	55.48**	2.72**	2.25**	2.21**	2.27**	27.71**	24.03**	42.41**	27.14**	0.33**	0.30**	0.28**	0.31**	31.45**	27.7**	34.63**	27.80**	**0.07****	**0.06****	**0.08****	**0.07****
σ^2GCA/ σ^2SCA		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Source of variation	df	Fruit girth (cm)				Pericarp thickness (mm)				Locules per fruit				Total soluble solids (%)				Titrable acidity (mg/100g)				Lycopene content (mg/100g)				Ascorbic acid (mg /100 g)			
		L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P	L1	L2	L3	P
Replications (R)	2	0.006	0.01	0.01	0.01	0.007	0.003	0.05	0.01	0.01	0.05	0.10	0.06	0.02	0.03	0.03	0.32	0.00005	0.0006	0.0001	0.0004	0.00004	0.0001	0.00002	0.0001	1.00	0.94	0.11	0.51
Lines (L)	6	5.83**	1.62**	1.40*	3.77**	2.43*	3.04**	2.11*	7.49*	1.96	2.82	0.68	4.95	0.39	0.41	0.32	0.88	0.01	0.03	0.01	0.05	0.0007	0.0009	0.0009	0.002	8.81	13.43	6.36	18.55
Testers (T)	3	6.74**	1.84*	1.73*	5.61**	0.45	0.35	0.49	1.27	3.92*	2.63	2.11	8.41	0.52	0.51	0.6	3.29	0.004	0.005	0.006	0.01	0.002	0.002	0.002	0.006	15.94**	18.86	25.40	56.79**
Lines × Testers	18	7.01**	0.47**	0.57**	0.91**	0.67**	0.73**	0.59**	1.95**	1.14**	1.40**	1.22**	3.50**	0.24**	0.23**	0.22**	0.76**	0.01**	0.01**	0.008**	0.02**	0.0008**	0.0007**	0.001**	0.002**	4.82**	9.89**	11.79**	13.68**
Environments (E)	2	-	-	-	0.21**	-	-	-	0.93**	-	-	-	0.73**	-	-	-	0.22**	-	-	-	0.002**	-	-	-	0.004**	-	-	-	11.04**
Lines × Envt.	12	-	-	-	0.11	-	-	-	0.04	-	-	-	0.25	-	-	-	0.68	-	-	-	0.003	-	-	-	0.0002*	-	-	-	5.02
Testers × Envt.	6	-	-	-	0.10	-	-	-	0.01	-	-	-	0.12	-	-	-	0.49*	-	-	-	0.0006	-	-	-	0.0001	-	-	-	1.70
Line × Testers × E	36	-	-	-	0.26**	-	-	-	0.02	-	-	-	0.13**	-	-	-	0.53**	-	-	-	0.003**	-	-	-	0.0001**	-	-	-	6.41**
Error	54	0.19	0.005	0.009	-	0.04	0.04	0.03	-	0.01	0.04	0.04	-	0.004	0.003	0.004	-	0.0001	0.0004	0.0009	-	0.00007	0.00009	0.00006	-	0.65	0.34	0.82	-
Pooled Error	162	-	-	-	0.006	-	-	-	0.04	-	-	-	0.03	-	-	-	0.52	-	-	-	0.005	-	-	-	0.00008	-	-	-	0.60
σ^2GCA		0.09**	0.10**	0.09*	0.09*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
σ^2SCA		0.12**	0.15**	0.18**	0.10**	0.20**	0.22**	0.18**	0.21*	0.37**	0.45**	0.39**	0.38**	0.08**	0.07**	0.09**	0.02**	0.003**	0.004**	0.002*	0.003**	0.0003**	0.0002**	0.0004*	0.0003**	1.34**	3.16**	3.57**	1.45*
σ^2GCA/ σ^2SCA		0.75	0.67	0.50	0.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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