IMPACT OF RECIPROCAL CROSS AND HETEROSIS PHENOMENON ON VARIOUS TOMATO TRAITS

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ABSTRACT

This research aimed to study the impact of the reciprocal cross and heterosis phenomena on numerous tomato (*Solanum lycopersicum* L.) characteristics. Fifty-one different traits were measured, including leaf, shoot, root, flower, fruit, yield and yield components, and physiochemical characteristics. The results showed that reciprocal crosses, such as plant mass, petal length, cone length, pistil length, fruit width, fruit length, single fruit weight, fruit flesh weight, seed and placenta weight, number of fruits locules, fruit calyx weight, number of days to flower, total sugar, ascorbic acid, anthocyanin, and total phenolic concentration, significantly influenced various traits. In addition, the results showed that several traits showed positive high parent heterosis, which are the sepal length, pistil length, flower fresh weight, flower dry weight, flower moisture content, number of clusters per plant, number of flowers per plant, number of flowers per cluster, number of fruits per cluster, fruits number per plant, total fruits weight per plant, leaf length, leaf fresh weight, leaf dry weight, number of branches per plant, plant height, plant mass, ascorbic acid, total carotene, and anthocyanin. These results will be significantly helpful for the future breeding program, especially for developing F1 cultivars with significant quality and quantity.

Keyword: reciprocal cross, heterosis, physiochemical characteristics, yield and yield components.

تأثير التهجين المتبادل وظاهرة قوة الهجين على الصفات المختلفة لمحصول الطماطة

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المستخلص

تم تهجين صنفين مختلفين من الطماطم (*Solanum lycopersicum* L.) بشكل متبادل لدراسة تاثير التهجين المتبادل وظاهرة قوة الهجين على العديد من الصفات لمحصول الطماطة. تم قياس 51 سمة مختلفة بما في ذلك الأوراق والمجموع الخضري والجذور والازهار والثمار والانتاجية والخصائص الفيزيوكيميائية. أظهرت النتائج أن كتلة النبات وطول النبات وطول الاسدية وطول المدقة وعرض الثمرة وطول الثمرة ووزن الثمرة الواحدة ووزن لحم الثمرة ووزن البذور والمشيمة وعدد الثمار في العنقود الواحد ووزن الكأس وعدد الايام المطلوبة للتزهير والسكر الكلي وحمض الأسكوربيك والأنثوسيانين والمحتوى الفينولي الكلي تاثرت معنويا بالتهجين المتبادل. بالإضافة إلى ذلك أوضحت النتائج أن العديد من الصفات قد تفوقت تفوقا معنويا وإيجابيًا للجيل الاول مقارنة بكلا الابوين كما في طول الاوراق التويجية وطول المدقة والوزن الرطب للزهرة والوزن الجاف للزهرة ومحتوى رطوبة الزهرة وعدد العناقيد لكل نبات وعدد الأزهار لكل نبات وعدد الزهور لكل عنقود وعدد الثمار لكل عنقود وعدد الثمار لكل نبات والوزن الإجمالي للثمار وطول الورقة ووزن الورقة الرطب والوزن الجاف للأوراق وعدد الفروع لكل نبات وارتفاع النبات وكتلة النبات وحامض الأسكوربيك وإجمالي الكاروتين والأنثوسيانين. ستكون لهذه النتائج اهمية كبيرة لبرامج التربية في المستقبل خاصة لتطوير أصناف الF1 ذو الجودة العالية.

الكلمات المفتاحية: التهجين المتبادل, قوة الهجين, الخصائص الفيزيوكيميائية, الانتاج ومكونات الانتاج.

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INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is a member of the Solanaceae family and is considered one of the most economical vegetables worldwide (7). Although the environment and growing situation impact many tomato traits significantly (8, 19), the genetic makeup of the cultivars studying a crucial role in tomato crop production by influencing numerous of traits (9,33,44). Thereby, studying the effect of the genetic studying the cultivars, especially F1 cultivars, performance increases the understanding of the cultivar requirements to maximize the overall production. Reciprocal cross and heterosis phenomena crucially influence tomato phenomena development; thereby, they impact tomato production significantly (27, 34). Besides the tomato crop, numerous of other economical crops such as wheat, maize, sunflower, cucumber, and pea that show essential effect of reciprocal cross and heterosis phenomenon on many agronomical traits that impact the ultimate yield directly or indirectly(28,35). The artificial crosses are made in a reciprocal cross, which is obtained by crossing two parental genotypes, one of which is female and the other is male, and vice versa (20). The reciprocal cross has several advantages and is considered an important tool to reveal the maternal effect on the following offspring (42). In addition, reciprocal crosses play an important role in breeding programs, especially in the development of new hybrids. For instance, a reciprocal crossing between two tomato cultivars' interactions could be modify the flowering time and plant architecture and ultimately yield an increase in the productivity of field tomatoes. Both female and male parents contribute some of their genes to their offspring (F1 hybrid), but the influence of female parents often extends beyond simple genetic transmission (37). The mechanisms of the reciprocal effect are still not fully understood. However, many factors have been suggested that might contribute in this phenomenon(32), such as the genetic and molecular makeup of the seeds, seed coat, endosperm, and embryo, maternal and paternal genotypes, and the epigenetic effects (16). Heterosis is a natural biological phenomenon which it refers to the heterozygote created by the hybridization of two or more parents with diverse genetic backgrounds (29). In terms of yield, growth rate, viability, and disease resistance(3), hybrids outperform their parents. In other words, it is defined as the deviation between F1 reciprocal crosses and their parental lines mean (35). Studying the influence of heterosis phenomenon on tomato crop started at the beginning of the last century which emphasized the significant impact of heterosis in various economical (45). Dominance, over-dominance, and epistasis are different models that have been proposed to explain heterosis, in which the heterosis becomes larger when the parents are more diverse (10). However, these factors are not enough to provide a full understanding of the heterosis phenomenon in terms of molecular basis. Furthermore, many studies have demonstrated that variation in gene expression is thought to constitute a significant source of phenotypic diversity at the molecular level (39). Plant breeders took advantage of the heterosis phenomenon for decades, but they had an incomplete consideration of the genetic properties. Later, plant breeders hypothesized that the genetic loci resulting from crossing two independent inbred lines because the genetic locus responsible for the enhanced performance may possess multiple factors which equally contribute to the final effect (41). Furthermore, the genetic composition of both parents has a significant effect on heterosis levels. Therefore, some traits displayed positive heterosis in some crossings and negative heterosis in others. This study aimed to reveal the influences of the reciprocal cross and heterosis phenomena on a number of traits in tomato crops(12).

MATERIALS AND METHODS

Plant Materials: This experiment was carried out during the 2021 growing season at the greenhouse belonging to the Department of Horticulture, College of Agricultural Engineering Sciences at the University of Sulaimani. Two different tomato cultivars (Indigo Ross x Santiam) were crossed reciprocally in the 2020.

Studied Traits

Both parents and the F1 and the reciprocal of the F1 (F1R) were compared for the 51 traits as following:

1. Leaf, shoot, and root traits

Leaf length (LFL) and leaf width (LFW) were measured by a standard ruler. Also, the number of leaflets (NLFL) was counted. A sensitive scale was used to measure the leaf fresh weight (LFW) directly. The leaf dry weight (LFDW) was estimated by placing the same leaves in an oven under 70 °C until the weight achieved stable values, then weighting them with a sensitive scale, and the leaf moisture (LFM) percentage was measured. The leaf area (LFA) was measured using Digimazier 5.7.0 software (22). Additionally, the number of branches per plant (NBPP) was measured. Also, plant height (PLH) was measured using a standard tape measure. The plant mass (PM) was calculated by weighting the whole dried plant, except the root, which was dried in an oven under 70 °C until the weight achieved stable values. Furthermore, the root length (RL) was measured using a standard ruler from the crown to the longest point of the root system. The number of root branches (NRB) and root mass (RM) was measured as the same as shoot parts.

2. Flower Parameter

Flower diameter (FLD), sepal length (SL), petal length (PL), cone length (CL), pistil length (PSL), flower dry weight (FLDW), and flower moisture content (FLM) were measured as flower traits.

3. Fruit parameters

Five fruits from each plant were measured for the following traits: fruit width (FW), fruit length (FL), single fruit weight (SFW), fruit flesh weight (FFW), seed and placenta weight (SPW), number of fruits locules (NFL), fruit calyx weight (FCW), fruit moisture (FM) and fruit volume (FV)

4. Yield and yield components parameters

The number of clusters per plant (NCP), number of flowers per plant (NFLP), number of flowers per cluster (NFPC), fruit number per plant (FNP), total fruit weight per plant (TFW), number of days to flower (NDFL), and number of days to fruit harvesting (NDFH) were measured.

5. Physiochemical parameters

One ripe fruit from each plant (three fruits per replication) was collected, then they were stored in the freezer (-18℃) immediately for one month without any physical or chemical treatments to ensure that all the genotypes were ready for the physiochemical tests. The fruits were thawed at refrigerator (4℃) temperature and the whole fruits were blended using an electric blender for 60 seconds in order to obtain the homogenized sample. Afterward, a sample test (100 ml per replication) was taken from the whole mixture to measure the following physicochemical properties. The pH of the tomato samples was determined using a microprocessor pH meter (model-pH 211-HNA Com. Italy), which had been previously standardized to pH 4 and pH 7 (25), The total soluble solids (TSS %) were measured using a portable hand refractometer (Erma Japan) which a drop of the samples was placed on the prism of the digital refractometer, and the total soluble solids were read in °Brix (25). The total Sugars (TS %) were determined according to (20) using a spectrophotometer set to 490 nm. The total Acidity (TA %) was measured using the titration procedure as mentioned in (5). The flavor Index (FI %) was calculated as mentioned in (27). The anthocyanins (ANC $mg\cdot100g^{-1}$ FW) were measured according to (5,11) using a spectrophotometer set to 535 nm absorbance wavelength. Chlorophyll a (Chla $\mu g\cdot mL^{-1}$ FW), chlorophyll b (Chlb $\mu g\cdot mL^{-1}$ FW), total chlorophyll (TChl $\mu g\cdot mL^{-1}$ FW), and total carotenoids (TCar $\mu g\cdot mL^{-1}$ FW) were determined according to(40,3).Which, the spectrophotometer was used with absorbance maxima reading at 663.6 nm for Chla, 646.6 nm for Chlb, and 470.0 nm for carotenoids. The lycopene (LYC $mg\cdot kg^{-1}$ FW) concentration was determined according to (4) . Using a spectrophotometer with 503 nm absorbance wavelength. The ascorbic acid (AA $mg\cdot100g^{-1}$ FW) concentration was determined according to the (34) using spectrophotometer with 243 nm absorbance wavelength. The total phenol concentration (TPC $mg\cdot100g^{-1}$ FW) was estimated using a spectrophotometer at 280 nm (5)

Experimental Design and Statistical Analysis: The trial was set up at the greenhouse using a complete randomized design (CRD) with three replications. Five plants from each cultivar were grown in plastic bags (18.5 cm in diameter and 45 cm in height). Three-quarters of the bags were filled with 50:50 peat moss and soil. In terms of trait measurements, three plants from the middle of each line were selected, and the average was used in the further statistical analysis. The least significant difference (LSD) and principal component analysis (PCA) were analyzed using R software. However, mid-parent (MD), mid-parent heterosis (MPH), and high-parent heterosis (HPH) were calculated as mentioned in (12). The average of the F1 and F1R was used for calculating MPH and HPH.

RESULTS AND DISCUSSION

1. Impact of reciprocal cross and heterosis phenomenon on leaf, shoot, and root traits: The genotypes (F1, F1R, and parental lines) showed significant variation in many leaves, shoot, and root traits (Figure 1). Several leaf traits such as LFL, LFW, NLFL, LFFW, LFDW, LFM, and LFA were studied to determine the impact of the reciprocal and heterosis on the progenies (Table 1). The results revealed that there were no significant differences between the parents, F1, and F1R, for approximately all the studied leaf traits except for LFDW and LFM. Additionally, there were no significant differences between the F1 and F1R (reciprocal effect) for all the traits. In terms of heterosis, positive MPH and HPH were observed in LFL (5.20 and 3.71%), LFFW (4.57 and 0.26%), and LFDW (74.26 and 72.55%), respectively, while only positive MPH was observed in the LFA trait (4.43%). These results indicate that the F1 and F1R had bigger leaves than the parents which significantly might enhance the overall yield. Many studied emphasized that the leaf morphology and leaf area played a significant role in increasing yield and accumulation of phytochemical substance in tomato fruits (27,37). Furthermore, the genotypes showed significant variation for all the shoot traits, NBPP, PLH, and PM (table 1). Both parents did not show statistical differences in NBPP and PM characteristics, whereas they were significantly different in PLH trait which the P1 was superior to P2 (86.77 and 51.00cm, respectively). In addition, reciprocal effects were only detected in PM characteristics, where F1 was significantly superior to F1R (55.89 and 28.62 g respectively). In terms of heterosis, positive MPH and HPH were observed for NBPP (127.12 and 99.45%), PLH (32.70 and 5.35%), and PM (219.03 and 148.27%) traits. Regarding the root traits, the results showed that the genotypes were significantly varied for RL, NRB, and RM traits. Both parents (P1 and P2) were significantly different in NRB and RM. Additionally, negative MPH and HPH were observed for all the root traits which mean that the progenies had smaller root system than the parents (Table 1). Regarding the biomass traits, the results showed a reciprocal effect only for the PM, while positive heterosis was detected for LFL, LFFW, LFDW, LFA, NBPP, PLH, and PM (Table 1). These traits crucially impact plant size and architecture. Although the exact etiology of heterosis is unknown, single gene expression may be capable of causing such a scenario. A study discovered that tomato plants with mutations in SINGLE FLOWER TRUSS (SFT), which is responsible for the flowering hormone florigen, flower late, become extremely large, and produce few flowers and fruits, but when heterozygous, yields are dramatically increased because the heterozygous gene enhances side branches and change the plant architecture, ultimately increasing yield (21). Furthermore, many studied proved that the heterosis phenomenon is strongly associated with the genetic makeup of the parent lines which in a study, hybrid vigor was observed in 29 distinct F1s derived from 169 Arabidopsis crossings (27). In addition, other researchers found strong positive heterosis in stem size and plant height of other crops, such as the sunflower plant, for instance (18). Many other studies showed the significant impact of plant architecture on yield in tomato crops(18,33).

Table 1. Mean comparison of the studied genotypes, both parents (P1 and P2) and both progenies (F1 and FR1), and values of LSD, mid parent values (MP), mid parent heterosis (MPH), and high parent heterosis (HPH) for the studied leaf, shoot, and root traits leaf length (LFL), leaf width (LFW), number of leaflet (NLFL), leaf weight (LFFW), leaf dry weight (LFDW), leaf moisture (LFM), leaf area (LFA), number of branches per plant (NBPP), plant height (PLH), plant mass (PM), root length (RL), number of root branches (NRB), root mass (RM).

Variables	P1	P2	F1	F1R	LSD (0.05)	MP	MPH (%)	HPH (%)
LFL (cm)	16.19^{a}	15.73^{a}	16.65^{a}	16.93^{a}	2.63	15.96	5.20	3.71
LFW (cm)	11.15^{a}	11.23^{a}	10.28^{a}	11.28^{a}	3.31	11.19	-3.66	-4.01
NLFL	12.01^{a}	11.13^{a}	8.68^{a}	8.71^{a}	3.47	11.57	-24.85	-27.6
LFFW (g)	7.12^{a}	7.76^{a}	7.42^{a}	8.14^{a}	3.28	7.44	4.57	0.26
LFDW (g)	1.02^{ab}	1.00^{c}	1.69^{ab}	1.83^{a}	0.68	1.01	74.26	72.55
LFM (%)	86.07^{a}	87.12^{a}	76.58^{b}	77.52^{b}	4.53	86.60	-11.02	-11.56
LFA (cm^2)	75.26^{a}	90.38^{a}	83.15^{a}	89.82^{a}	16.94	82.82	4.43	-4.31
NBPP	5.50^{b}	4.16^{b}	10.61^{a}	11.33^{a}	2.99	4.83	127.12	99.45
PLH (cm)	86.77^{a}	51.00^{b}	91.16^{a}	91.66^{a}	17.87	68.89	32.70	5.35
PM (g)	17.02^{b}	9.47^{b}	55.89^{a}	28.62^{b}	19.23	13.25	219.03	148.27
RL (cm)	43.83^{a}	40.5^{ab}	23.33^{ab}	22.33^{b}	21.47	42.17	-45.86	-47.91
NRB	1.83^{b}	4.83^{a}	2.83^{ab}	3.66^{ab}	2.54	3.33	-2.55	-32.82
RM (g)	6.31^{a}	3.82^{b}	1.77^{b}	1.80^{b}	2.08	5.07	-64.76	-71.71

Different letters indicate significant difference ($P < 0.05$)

Figure 1. the genotypes mature plants P1 (Indigo Ross), F1, F1 Reciprocal, and P2 (Santiam)

2. Impact of reciprocal cross and heterosis phenomenon on floral traits: Furthermore, the results revealed that the genotypes differed significantly in several of the floral traits (Figure 2). Both parents (P1 and P2) were significantly different in FLD (20.45 and 23.76 mm), PL (9.45 and 11.22 mm), CL (6.07 and 7.37 mm), and FLM (83.2 and 85.9%) (Table 2). In addition, significant differences were observed between F1 and F1R in PL (8.94 and 11.00 mm), CL (5.05 and 6.67 mm), and PSL (6.11 and 9.89 mm), respectively. Furthermore, the MPH and HPH were calculated in order to estimate the heterosis values for each variable (Table 1). The FLD, SL, PSL, FLFW, FLDW, and FLM showed positive MPH (2.90, 30.73, 26.88, 28.95, 25.00, and 2.52%), respectively. Moreover, SL, PSL, FLFW, FLDW, and FLM showed positive HPH (17.78, 25.00, 16.67, 25.00, and 0.95%) respectively. Although there is no detail about the influence of reciprocals and heterosis on flower traits(24), a study found a positive MPH and HPH in the flower dimeter of sunflower in many different crosses (18). In addition, a study showed that the reciprocal cross significantly influenced flower traits in Gladiolus. Also, a negative and a positive heterosis were observed in various flower traits; peduncle length, floret diameter, and floret length depending on the parental crossing direction (6). Another study on Phalaenopsis observed that the reciprocal cross significantly affected flower width and length (43).

Table 2. Mean comparison of the studied genotypes, both parents (P1 and P2) and both progenies (F1 and FR1), and values of LSD, mid parent values (MP), mid parent heterosis (MPH), and high parent heterosis (HPH) for the studied flower traits flower dimeter (FLD), sepal length (SL), petal length (PL), cone length (CL), pistil length (PSL), flower fresh weight (FLFW) flower dry weight (FLDW), flower moisture content (FLM).

Variables	P1	P2	F1	F1R	LSD (0.05)	MP	MPH (%)	HPH (%)
FLD (mm)	20.45[b]	23.76[a]	22.38[ab]	23.11[a]	2.631	22.11	2.9.00	-4.27
SL (mm)	6.72[a]	8.38[a]	9.47[a]	10.27[a]	5.36	7.55	30.73	17.78
PL (mm)	9.45[b]	11.22[a]	8.94[b]	11.00[a]	1.54	10.34	-3.53	-11.14
CL (mm)	6.07[b]	7.37[a]	5.05[c]	6.67[ab]	0.97	6.72	-12.8	-20.49
PSL (mm)	6.21[b]	6.40[b]	6.11[b]	9.89[a]	1.46	6.31	26.88	25.00
FLFW (mg)	0.17[b]	0.21[ab]	0.25[a]	0.24[a]	0.04	0.19	28.95	16.67
FLDW (mg)	0.02[a]	0.02[a]	0.02[a]	0.03[a]	0.01	0.02	25.00	25.00
FLM (%)	83.20[b]	85.9[a]	87.09[a]	86.34[a]	2.39	84.55	2.56	0.95

Different letters indicate significant difference ($P < 0.05$)

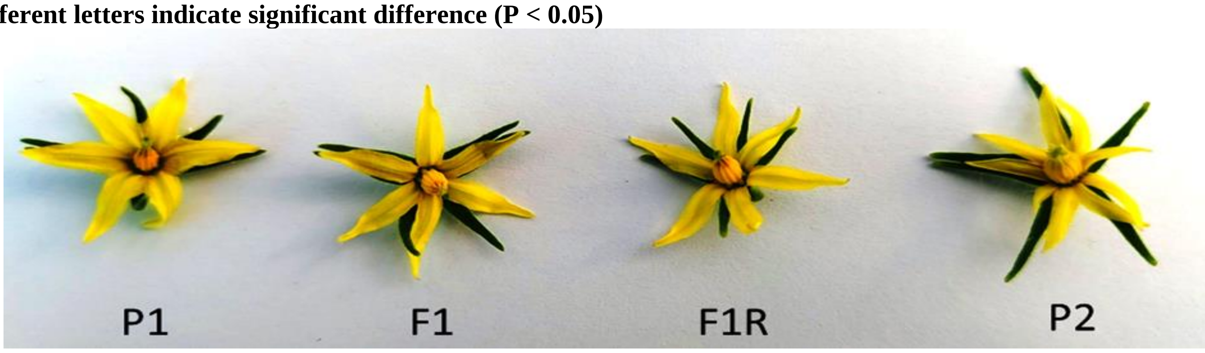

Figure 2. the genotypes flowers P1 (Indigo Ross), F1, F1 Reciprocal, and P2 (Santiam)

3. Impact of reciprocal cross and heterosis phenomenon on fruit traits

The genotypes revealed significant differences in many different fruit traits (Figure 3). Except for FM, the genotypes showed considerable variation in practically all of the fruit attributes studied: FW, FL, SFW, FFW, SPW, NFL, FCW, and FV (Table 3). The parents had a broad range of variation, with the P2 considerably outperforming the P1 for all fruit attributes except FM. In addition, P2 differed considerably across all genotypes in FV. Furthermore, the results demonstrated that the fruit features were heavily impacted by the reciprocal effect, with F1 significantly outperforming F1R for all tested fruit traits except for FM and FV. Additionally, positive MPH was observed in FW, FL, FCW, and FM (6.79, 6.01, 19.05, and 0.06 %, respectively), where some of these traits showed high heterosis values .However, negative HPH was observed for the FL (25.91 %) trait only (Table 3). The eventual yield's size and quality are greatly influenced by the fruit's characteristics. With the exception of FM and FV, substantial differences were seen for the reciprocal cross for other fruit attributes, where the F1 was consistently superior to the F1R for all the cases (Table 3). These results agreed with the results of another study which reported that more than 10 traits of tomato fruit were highly influenced by reciprocal crosses(14). In addition, another study found that the seed weight was significantly affected by reciprocal hybrids, which mentioned that the seed weight was significantly changed according to the parents' crosses in Arabidopsis(28). In addition, a positive heterosis was observed for FW, FL, FCW, and FM (Table 3). A study reported that a highly significant heterosis of positive was found for fruit length (32.7 and 15.5%) and fruit weight (48.7 and 45.0%) over the mid and better parents, respectively. Furthermore, positive significant heterosis was observed over the mid and better parents(38) for fruit length

(8.9%), fruit width (8.7 and 7.9%), and fruit weight (14.3 and 12.5%), respectively (17). However, positive significant heterosis was identified in some crosses for fruit locule numbers, while we observed negative heterosis in the current study with a significant reciprocal effect (30). Furthermore, positive and strong phenotypic and genotypic correlations were found between fruit yield per plant and the characteristics of fruit number per plant, fruit weight, and fruit thickness, which resulted in increased yield(40) .

Table 3. Mean comparison of the studied genotypes, both parents (P1 and P2) and both progenies (F1 and FR1), and values of LSD, mid parent values (MP), mid parent heterosis (MPH), and high parent heterosis (HPH) for the studied fruit traits fruit width (FW), fruit length (FL), single fruit weight (SFW), fruit flesh weight (FFW), seed and placenta weight (SPW), number of fruits locules (NFL), fruit calyx weight (FCW), fruit moisture (FM), fruit volume (FV).

Variables	P1	P2	F1	F1R	LSD (0.05)	MP	MPH (%)	HPH (%)
FW (mm)	23.96^{c}	37.78^{a}	36.00^{a}	29.93^{b}	3.24	30.87	6.79	-12.74
FL (mm)	23.52^{c}	32.35^{a}	31.71^{a}	27.52^{b}	2.81	27.94	6.01	-8.45
SFW (g)	7.94^{d}	30.61^{a}	23.63^{b}	14.29^{c}	4.70	19.28	-1.63	-38.06
FFW (g)	6.78^{d}	23.44^{a}	18.88^{b}	11.12^{c}	3.88	15.11	-0.73	-36.01
SPW (g)	1.15^{d}	7.16^{a}	4.74^{b}	3.17^{c}	1.01	4.16	-4.81	-44.76
NFL	2.00^{c}	5.33^{a}	3.33^{b}	2.16^{c}	0.81	3.67	-25.10	-48.5
FCW (g)	0.17^{c}	0.25^{b}	0.31^{a}	0.19^{c}	0.05	0.21	19.05	0.00
FM (%)	94.04^{a}	93.64^{a}	93.96^{a}	93.83^{a}	0.95	93.84	0.06	-0.15
FV (cm3)	18.33^{b}	48.00^{a}	18.45^{b}	10.61^{b}	8.14	33.17	-56.19	-69.73

Different letters indicate significant difference ($P < 0.05$)

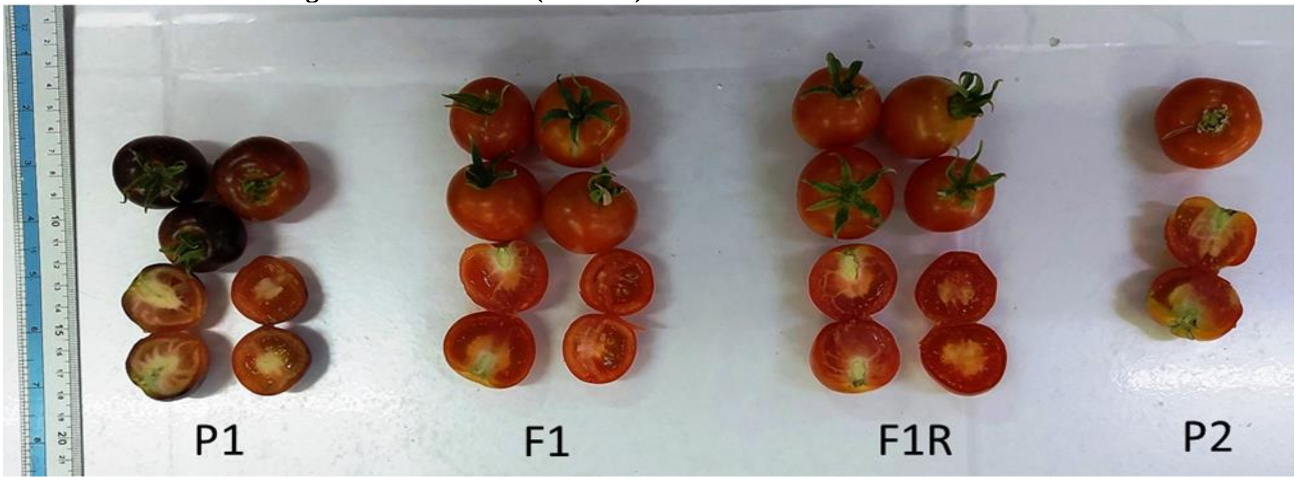

Figure 3. the genotypes fruits P1 (Indigo Ross), F1, F1 Reciprocal, and P2 (Santiam)

4. Impact of reciprocal cross and heterosis phenomenon on yield and yield components traits: To investigate the influence of reciprocal crosses and heterosis phenomenon on yield and yield components, the NCP, NFLP, NFLC, NFPC, FNP, TFW, NDFL, and NDFH traits were measured. Our results revealed that the genotypes showed significant differences in yield and yield component traits. Significant positive heterosis was observed(24). Both parents did not show significant variation for all the studied variables except for the NFPC and NDFH, where both parents were significantly varied (Table 4). In addition, the results showed that there were no significant differences between the F1 and F1R for most of the yield and yield components except NDFL, where the F1R (27.66 days after transplanting) was superior to the F1 (22.33 days after transplanting). The F1 surpassed the F1R in several traits, including NCP, NFLP, NFPC, FNP, and TFW, with the exception of the NDFH characteristic, where the F1R logged more necessary days, albeit neither exceeded the statistically significant level. However, all the yield and yield component traits such as NCP (274.01 and 211.57%), NFLP (462.49 and 251.73%), NFLC (61.69 and 37.79%), NFPC (112.48 and 45.03%), FNP (385.81 and 252.34%), and TFW (124.77 and 53.67%) showed positive MPH and HPH, respectively, which clearly showed that the F1 performance was superior on the parents for all the mentioned traits. Whereas, NDFL (-23.08 and -23.47%) and NDFH (-15.39 and -23.88%) showed negative heterosis values which means that the F1 was earlier than the parents (Table 4). These findings are agreed with many different studies that they report that the reciprocal crosses and heterosis phenomenon influenced various yield and yield component traits in tomato plants(38), such as number of fruits and total yield; additionally, they stated that the genetic make-up of parents played a significant role in expressing the heterosis phenomenon in various traits(19,2). Furthermore, other studies showed that there are many QTL that control the heterosis effect that influences yield and yield components and mentioned that epistasis among loci without detectable main effects plays an important role in controlling heterosis in the yield of mustard(1,9). Aside from the previously cited reasons for heterosis, a study discovered that heterozygosity for loss-of-function alleles of SINGLE FLOWER TRUSS (SFT), the genetic originator of the flowering hormone (florigen) in tomatoes, increases yield by up to 60%. Yield over dominance caused by SFT heterozygosity is common, occurring across a wide range of genetic backgrounds and conditions(23). However, according to another study, *sft* heterozygosity enhances plant architecture, resulting in a considerable increase in yield (21). Furthermore, in a tomato study, it was found that a highly significant positive heterosis was found for many yield and yield component traits (23), such as flowers per cluster (53.1 and 37.2%), fruits per cluster (38.9%), and yield per plant (34.9%) over the mid and better parents, respectively. Moreover, positive significant heterosis was observed for flowers per cluster (7.4%), fruits per cluster (10.0 and 10.0%), and yield per plant (24%), over the mid and better parents, respectively(17).

Table 4. Mean comparison of the studied genotypes, both parents (P1 and P2) and both progenies (F1 and FR1), and values of LSD, mid parent values (MP), mid parent heterosis (MPH), and high parent heterosis (HPH) for the studied yield and yield components traits number of cluster per plant (NCP), number of flower per plant (NFLP), number of flower per cluster (NFPC), fruit number per plant (FNP), total fruit weight per plant (TFW), number of days to flower (NDFL), number of days to fruit harvesting (NDFH).

Variables	P1	P2	F1	F1R	LSD (0.05)	MP	MPH (%)	HPH (%)
NCP	11.50^{b}	7.66^{b}	41.00^{a}	30.66^{a}	14.21	9.58	274.01	211.57
NFLP	82.00^{b}	20.55^{b}	331.83^{a}	245^{a}	125.3	51.28	462.49	251.73
NFLC	7.00^{b}	4.93^{b}	9.86^{a}	9.43^{a}	2.42	5.97	61.69	37.79
NFPC	4.93^{b}	1.80^{c}	7.30^{a}	7.00^{a}	1.70	3.37	112.48	45.03
FNP	15.16^{b}	6.83^{b}	57.00^{a}	49.83^{a}	23.52	11.00	385.81	252.34
TFW (g)	139.11^{c}	378.74^{bc}	702.84^{a}	461.15^{ab}	264.06	258.93	124.77	53.67
NDFL (day)	32.66^{a}	32.33^{a}	22.33^{b}	27.66^{a}	5.01	32.5	-23.08	-23.47
NDFH (day)	77.00^{b}	96.33^{a}	72.33^{c}	74.33^{c}	2.66	86.67	-15.39	-23.88

Different letters indicate significant difference ($P < 0.05$)

5. Impact of reciprocal cross and heterosis phenomenon on physiochemical traits: Several physiochemical characteristics were measured to investigate the influence of the reciprocal cross on progenies and estimate the heterosis values for each characteristic. The studied variables included pH, TSS, TS, TA, FI, AA, Lyco, Chla, Chlb, TChl, TCar, ANC, and TPC (Table 5). Except for Chla, Chlb, and TChl, where no significant differences were found, the genotypes exhibited significant variance for all variables. Furthermore, the results indicated that P1 was considerably superior to P2 in TS, AA, ANC, and TPC characteristics, whereas P2 was significantly superior to P1 in TA and Lyco traits. However, there were no significant variations between both parents in pH, TSS, FI, Chla, Chlb, TChl, and TCar (Table 5). In addition, reciprocal effects were identified in various physicochemical parameters, with F1 showing significant superiority to F1R in TS, AA, and TPC traits, whereas F1R was clearly superior to F1 in ANC. Additionally, the F1 was considerably superior to both parents in AA, ANC, and TPC variables, but the F1R was significantly superior to both parents only in ANC (Table 1). Furthermore, positive MPH and HPH were observed in AA (36.08 and 17.69%), TCar (39.05 and 15.87%), and ANC (646.40 and 385.26%), respectively. However, only positive MPH was observed in TS (14.95%), TA (7.69%), Chla (1.61%), and TPC (12.08%) (Table 5). The physiochemical properties are essential for the tomato crop because they are responsible for the flavor and nutritional value of the tomato fruits. According to a study, choosing the female and male cultivars during the cross process has a substantial impact on the fruit quality and the possibility of using fruit composition to benefit from the heterosis phenomenon (13). Another study found that 45 of the 47 tomato physiochemical compounds investigated showed either over-dominance or over-recessive patterns, which could explain the heterosis and reciprocal effect on these features when crossing the cherry tomato with the large tomato (9). Additionally, several physiochemical traits showed either MPH or both MDH and HPH, such as TS, TA, AA, Chla, TCar, ANC, and TPC (Table 5). Research reported that there was no significant difference between reciprocal crosses for chlorophyll content for most of the crosses, which agrees with our finding; however, significant heterosis (122.86 and 156.20%) was only observed for two genotypes related to the mean of parents for Chla and Chlb contents, respectively, while we observed negative heterosis for chlorophyll contents (15). In addition, positive high significant heterosis was found for ascorbic acid and TSS in a 15 x 15 diallel tomato study in which the ascorbic acid results agree with our finding, but the results for the TSS do not (9). Furthermore, another study found positive significant heterosis for TSS, titratable acidity, lycopene, carotene, and ascorbic acid; however, all of these findings were observed in some of the crosses used in the study, while others showed only minor negative heterosis (30).

Table 5. Mean comparison of the studied genotypes, both parents (P1 and P2) and both progenies (F1 and FR1), and values of LSD, mid parent values (MP), mid parent heterosis (MPH), and high parent heterosis (HPH) for the studied physiochemical traits pH, total soluble solid (TSS), total sugar (TS), total acidity (TA), flavor index (FI), ascorbic acid (AA), lycopene (Lyco), chlorophyll a (Chla), chlorophyll b (Chlb), total chlorophyll (TChl), total carotene (TCar), anthocyanin (ACN), and total phenolic concentration (TPC).

Variables	P1	P2	F1	F1R	LSD (0.05)	MP	MPH (%)	HPH (%)
PH	4.75^{ab}	4.96^{a}	4.33^{b}	4.43^{ab}	0.62	4.86	-9.78	-11.69
TSS (%)	5.38^{ab}	5.90^{a}	4.96^{ab}	4.8^{b}	0.97	5.64	-13.48	-17.29
TS (%)	2.89^{ab}	1.86^{c}	3.56^{a}	1.9^{bc}	1.00	2.38	14.95	-5.54
TA (%)	0.29^{b}	0.49^{a}	0.42^{ab}	0.42^{ab}	0.15	0.39	7.69	-14.29
FI	1.20a	1.09^{ab}	1.02^{b}	1.03^{ab}	0.17	1.15	-10.48	-14.58
AA (mg/100g)	19.79^{b}	14.44^{c}	25.91^{a}	20.67^{b}	3.17	17.12	36.08	17.69
Lyco mg/kg	22.39^{c}	34.67^{a}	30.36^{ab}	26.15^{bc}	4.88	28.53	-0.96	-18.5
Chla (µg/ml)	0.36^{a}	0.26^{a}	0.30^{a}	0.33^{a}	0.38	0.31	1.61	-12.5
Chlb (µg/ml)	0.47^{a}	0.31^{a}	0.31^{a}	0.45^{a}	0.40	0.39	-2.56	-19.15
TChl (µg/ml)	0.84^{a}	0.58^{a}	0.62^{a}	0.78^{a}	0.76	0.71	-1.41	-16.67
TCar (µg/ml)	0.42^{b}	0.63^{ab}	0.65^{a}	0.81^{a}	0.23	0.53	39.05	15.87
ANC (mg/100g)	7.26^{c}	2.18^{d}	34.35^{b}	36.11^{a}	1.29	4.72	646.4	385.26
TPC (mg/100g)	98.04^{b}	75.43^{d}	106.26^{a}	88.16^{c}	7.55	86.74	12.08	-0.85

Different letters indicate significant difference (P < 0.05)

6. Principle component analysis

The PCA was conducted to determine the relationship between the cultivars. The first two main components (PC1 and PC2) together explained 83.7% of the observed variation and were thus represented in two dimensions (Figure 4). PC1, plotted on the horizontal axis, illustrated the highest proportion of the variance (47.2%), while PC2, plotted on the vertical axis, accounted for a further 36.5% of the total variation. In addition, the PCA grouped the genotypes into three distinct groups: P1, P2, and both F1 and F1R (Figure 1).

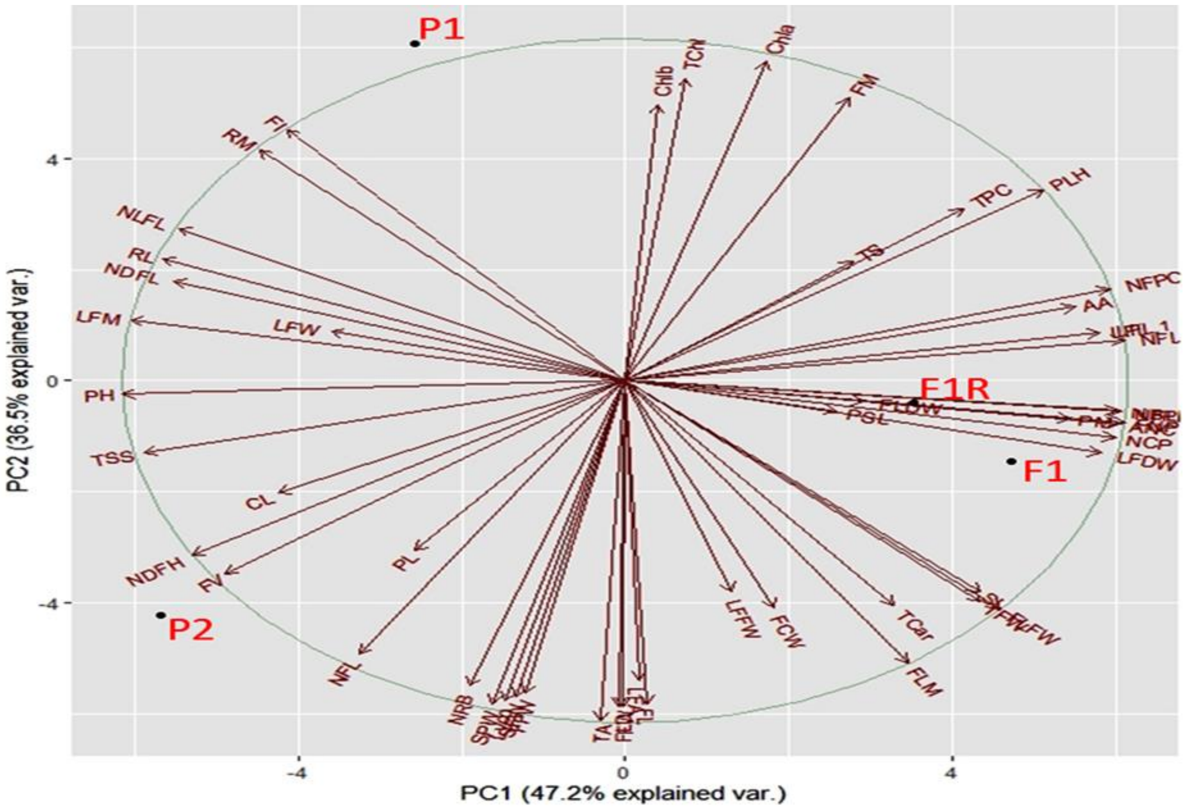

Figure 4. PCA biplot showing the distributions of the four tomato genotypes and the 51 studied variables: leaf length (LFL), leaf width (LFW), number of leaflet (NLFL), leaf weight (LFFW), leaf dry weight (LFDW), leaf moisture (LFM), leaf area (LFA), number of branches per plant (NBPP), plant height (PLH), plant mass (PM), root length (RL), number of root branches (NRB), root mass (RM), flower dimeter (FLD), sepal length (SL), petal length (PL), cone length (CL), pistil length (PSL), flower fresh weight (FLFW) flower dry weight (FLDW), flower moisture content (FLM), fruit width (FW), fruit length (FL), single fruit weight (SFW), fruit flesh weight (FFW), seed and placenta weight (SPW), number of fruit locules (NFL), fruit calyx weight (FCW), fruit moisture (FM), fruit volume (FV), number of cluster per plant (NCP), number of flower per plant (NFLP), number of flower per cluster (NFPC), fruit number per plant (FNP), total fruit weight per plant (TFW), number of days to flower (NDFL), number of days to fruit harvesting (NDFH), pH, total soluble solid (TSS), total sugar (TS), total acidity (TA), flavor index (FI), ascorbic acid (AA), lycopene (Lyco), chlorophyll a (Chla), chlorophyll b (Chlb), total chlorophyll (TChl), total carotene (TCar), anthocyanin (ACN), and total phenolic concentration (TPC).

Also, the results showed that both parents (P1 and P2) differed from each other. However, their progenies (F1 and F1R) showed narrow variation from each other, indicating that only some of the traits showed reciprocal effects while most of the traits did not. Furthermore, the PCA revealed the correlated variables, and all the correlated variables were directed in the same direction. Additionally, it showed the impact of the studied traits on the genotype distribution (Fig 1). The genetic diversity and geographical isolation play crucial role in determination of cultivar attributes (26). In addition, molecular evidence showed that hybrid vigor in maize correlates with the genetic distance between the parental inbred lines. Which, could be true for all crops (31, 36).

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