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Research Article

Genetic Analysis and Combining Ability for Improving Yield and Salt Tolerance in Tomato

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Abstract:

The experiment was planted on tomato were conducted at a private farm in Village in Kafr el-Sheikh city, Kafr el-Sheikh Governorate the North Delta region is considered one of the most important areas in Egypt affected by salts. Salinity is a significant constraint that limits tomato productivity and tomatoes are only moderately salt-tolerant. Five parental cultivars (Edkawy, Castle Rock, CLN2498E, SuperMarmand, Super Strain B). Diallel crosses to produce F1 hybrids, leading to evaluation of genotypes. The experiment was laid out in Completely Randomized Design (C.R.D.) with three replications, A two-factor pot experiment in a greenhouse (2022/2023 and 2023/2024), Factor A: 15 genotypes (5 parents + 10 hybrids) and Factor B: Four salinity treatments (control plus three salinity levels) Design with Each genotype-treatment combination replicated three times (total: 180 pots). Results Significant positive GCA for chlorophyll Castle Rock (P2) and SuperMarmand (P4) were strong general combiners. Strong SCA Hybrids such as P1×P3, P2×P3, and P3×P5 showed high SCA for chlorophyll and/or proline, revealing favorable specific combinations for stress tolerance through osmolyte accumulation. Na^+/K^+ Ratio and Ascorbic Acid SCA variances generally exceeded GCA, indicating non-additive gene action was predominant. Nevertheless, some parents displayed positive GCA effects for ascorbic acid content, while favorable SCA for reduced Na^+/K^+ ratio and increased ascorbic acid appeared in crosses such as P1×P2, P2×P3, and P4×P5. Yield Traits SCA mean squares surpassed GCA under all conditions; low GCA/SCA ratios (<0.12) reinforce the dominance of non-additive gene action for yield, highlighting the importance of heterosis and hybrid development Breeding Objectives Efforts focus on developing F1 hybrids with both high yield and improved tolerance to salinity by analyzing gene actions and inheritance.

1. Introduction

Tomato (2n=2x=24) is a vital solanaceous crop in Egypt, cultivated on 375,000–500,000 feddans with an average yield of 17.3 tons per feddan (FAO, 2023). Tomatoes are valued for their nutritional content, especially vitamins A and C, and are essential for food security. However, soil salinity is a major abiotic stress limiting tomato productivity, affecting over one-third of irrigated land globally and projected to impact more than half by 2050 (FAO, 2011; Zhao et al., 2020). Salinity impairs plant growth through osmotic stress, imbalance, and metabolic disturbances, with tomatoes being only moderately salt-tolerant.

To address increasing demand and salinity challenges, breeding programs focus on developing high-yielding, salt-tolerant hybrids. F1 hybrids have demonstrated superior yield and quality traits (Soliman et al., 2013; Shalaby, 2013), and their evaluation relies on combining ability analysis to understand additive (GCA) and non-additive (SCA) genetic effects (Griffing, 1956).

Despite the presence of salt-tolerant wild relatives, incorporating their genes into elite lines remains challenging due to complex inheritance patterns (Cuartero et al., 2006). Tomato From vegetative development to reproduction, commercial tomato varieties are only mildly salt sensitive throughout all phases of growth. Most crops need irrigation; nevertheless, poor irrigation management causes salinization of soil and water supplies High concentrations of the salt ions Na+ and Cl− in the soil solution are frequently the cause of salt stress, which has detrimental effects on plants through primary stresses like osmotic stress and ion imbalance as well as secondary stresses like oxidative stress and metabolic abnormalities (Yang and Guo, 2018a). Water availability is decreased when there is an excessive buildup of Na+ in the soil because it raises the osmotic pressure, lowers the water potential, and decreases root water uptake (Julkowska and Testerink, 2015; van Zelm et al., 2020). Additionally, the activity of many K+-dependent enzymes in the cells is inhibited due to the disruption of the Na+/potassium ion (K+) ratio (Wu et al., 2018). The main way that chloride damages plants is by disrupting their uptake or metabolism, which results in an imbalance. Particularly by knowledge of the pattern of inheritance of economic features, many crops have been genetically enhanced with tremendous success. Furthermore, necessary for a successful breeding program is an understanding of genetic architecture as the parental source. Selection programs should help with optimum progress if additive gene action explains most of the genetic variance. Conversely, a quite strong non-additive gene activity indicates, based on (Singh and Choudhary 2005), that the generation of F1 hybrids should be given some thought. Nowadays, most vegetable crops are produced commercially using F1 hybrids somewhat extensively. Furthermore, preferred are hybrids for their homogeneity, early maturity, great yield potential, and tolerance to biotic and abiotic pressures. Tomato hybrids are in great demand mostly for these reasons. Choosing cultivars and hybrids for a given area depends on both yield and fruit qualities. For both producers and consumers, more focus.

Should this be on cultivar improvement for these features. Hybrids produced by plant breeding yield more than free-pollinated cultivars.

This research aims to evaluate genetic traits, combining abilities, and inheritance patterns in tomato hybrids under varying salinity conditions. The goal is to identify and develop hybrids that combine high yield with enhanced salt tolerance, thereby supporting sustainable tomato production in salinity-affected regions.

2. Materials and Methods

2.1. Diallel analysis

2.1.1. The estimates of combining ability

The data were analyzed to verify the importance of differences Factor A only lists 5 parents, named: Edkawy (P1), Castle Rock (P2), CLN2498E (P3), Super Marmand (P4), Super Strain B (P5) and their 10 hybrids). The number mismatch needs explanation or correction, according to Snedecor and Cochran (1967). Analysis of variance was calculated for each character. Then, the differences between genotypes were further partitioned to general combining ability (GCA) and specific combining ability (SCA), i.e., Griffing analysis (1956) (Method 2; Model 2), as a fixed model. Variances due to general and specific combining abilities were estimated. The mathematical model for single hybrids value (xii), as given by Griffing (1956).

Baker (1978) and changed it by HungandHolland (2012). Analyses of statistics used an equation from) in order to find out the GCA/(GCA+SCA) ratio: 2 2GCA/2 2GCA + 2SCA (1) where 2 2GCA is the difference between the GCA effects and the mean square of the GCA, and 2SCA is the difference between the SCA effects and the mean square of the SCA. The overall genetic variance hybrid F1 hybrids is equal to twice the GCA component plus the SCA component. The closer this ratio is to one, the more of a specific hybrid's performance may be predicted based on GCA alone.

2.2. Data recorded

2.2.1. Chemical characteristics

a) Total chlorophyll content

The total chlorophyll content of the fifth leaf from the plant apex was measured using the SPAD-501, a portable leaf chlorophyll meter (Minolta Corp) designed for assessing greenness in fully expanded leaves without causing damage (Marqurad and Timpton, 1987).

b) Proline content

To determine proline for free, 0.5 g of each sample was mixed with 10 ml of 3% sulfosalicylic acid. We used Whatman No. 1 filter paper to filter the homogenate. In a test tube, 2 ml of the filtrate were mixed with 2 ml of acid ninhydrin and 2 ml of glacial acetic acid and left to react for an hour at 100°C. An ice bath ended the reaction. The prior mixture was taken out with 4 ml of toluene and mixed well for 15 to 20 seconds. The aqueous phase was warmed to room temperature and toluene with chromophore was sucked out. We used toluene as a blank to test the solution's optical density at 520 nm. According to Bates et al. (1973), the standard curve was used to find proline. The amount of proline was given as mg/g of dried leaf tissue.

c) Na+ and K+ determination

Leaves and roots of plants were dried, and 0.1 g of each sample was digested with H_2SO_4 and H_2O_2 (Evenhuis and de Waard, 1980). The quantification of Na and K ions was done using a flame photometer.

2.2.2. Total yield/plant and Ascorbic acid content

*a) Number of fruits the total fruit number/plant***.** It was calculated from all harvested fruits.

*b) Fruit weight***.** It was calculated from all harvested fruits for the whole season.

*c) Ascorbic acid content***.** It was determined by titration with 2, 6 di-chlorophenol indophenol blue dye (Cox and Pearson, 1962). It was expressed as mg ascorbic acid / 100g fresh weight of fruits.

2.3. Experimental design

A two-factor pot experiment was conducted under a private greenhouse in Kafr Elsheikh city from October 2023 to March 2024. The experiment was laid out in Completely Randomized Design (C.R.D.) with three replications. Treatments: Factor A: Fifteen tomato varieties, including five parents and ten hybrids. Factor B: One control and three salinity levels (freshwater 500 ppm (control) Moreover, three salinity levels, 4000, 6000, and 8000 ppm) were used as experimental treatments in this experiment. The Fifteen genotypes were transplanted into black colored plastic pots with a depth of 42 cm and an inner diameter of 40 cm. Each container was filled with 18 kg of pure, ion-free sand and replanted with a single tomato seedling. The transplants were maintained under optimal conditions for two weeks until the root system was fully restored and securely established in the growing soilless. Subsequently, three treatments were administered over a period of 7 weeks. The transplants were divided into 3 replications for each therapy, with 15 pots assigned to each replication. There was a total of 180 therapies, which were categorized based on three parameters. The drip irrigation system was used. Fertigation was carried out according to recommendations.

3. Results

3.1. Combining ability for chemical content characteristics

Analyses of variance for general combining ability (GCA) and specific combining ability (SCA) in chemical content characteristics (Tables 1, 2, 4, and 5) demonstrated considerable genetic variation among tomato genotypes grown in greenhouse conditions during the 2023/2024 season including under saline stress. For total chlorophyll content and proline content in leaves, SCA mean squares were consistently greater than GCA mean squares across all treatments (control, T1, T2, T3), with low GCA/SCA ratios (generally below 0.06). This pattern indicates a predominance of non-additive gene action (dominance and/or epistasis) in the inheritance of these traits. For proline, the GCA/SCA ratio was even negative under T1, suggesting highly specific genetic interactions unique to these treatment conditions.

Furthermore, parental GCA effects (Table 4) identified certain parents, such as P2 and P4, as strong general combiners for total chlorophyll content, exhibiting consistently positive and significant GCA effects across all treatments.

Conversely, P1, P3 and P5 showed negative GCA effects for chlorophyll, indicating poorer combining ability for this trait. Significant positive GCA effects for proline content were seen intermittently, suggesting that the ability to accumulate Osmo protectants like proline is more context-dependent and influenced by environmental conditions. Among hybrids, strong positive SCA effects for total chlorophyll content were recorded in combinations such as P1 × P3, P2 × P3 and P3 × P5 under all treatments, indicating the presence of highly favorable allele interactions in these crosses. In proline content, significant SCA effects (e.g., P1 × P3 and P2 × P3) highlight specific cross combinations beneficial for stress tolerance via osmolyte accumulation.

3.2. Na^+/K^+ ratio and ascorbic acid content

For Na^+/K^+ ratio and ascorbic acid content (Table 5), GCA and SCA effects also varied by genotype and treatment. The SCA variance was greater than GCA, reaffirming the predominant role of non-additive genetic effects. Both positive and negative GCA effects among parents suggest the possibility of selecting lines with either higher or lower ion accumulation or vitamin C content as required for breeding objectives. Notable hybrid combinations, such as P1 × P2, P2 × P3, and P4 × P5, showed significant SCA effects for both reduced Na^+/K^+ ratios and increased ascorbic acid, which are desirable for both stress tolerance and fruit quality K^+/Na^+ Ratio. Maintaining a favorable balance is critical for enzyme activity, protein synthesis, turgor maintenance, and metabolic competence. Plants achieve this by both restricting Na^+ uptake and actively retaining K^+ in the cytosol. Inheritance studies indicate that salt tolerance specifically the plant's ability to retain K^+ is primarily governed by additive genetic effects, this suggests strong potential for progress in breeding programs focused on these characteristics.3.2.1. General Information

All figures MUST be embedded in the main document in the final submission. All figures are numbered according to its sequence in the text. All figures must have captions. Do not include figure numbers, captions, or author names as part of the figure (as a photo). Captions should follow the figures in the main document. For multi-panel figures, the file must contain all data in one file. Composite figures must be submitted preassembled. Label identifications should appear in 14 pt Arial font in bold. If other labeling is included in your figure files, please make sure it will appear in a minimum size of 6pt type, with 9pt preferred, maintaining the same font for all figures submitted with your manuscript. Capitalize only the first word and proper nouns in each label. Scale bars should be inserted to indicate magnification. Photographic images should be clear and of high quality, cropped at right angles.

3.3. Yield components analysis

The evaluation of yield components (total fruit number and fruit weight per plant; Tables 3 and 6) again revealed that SCA mean squares surpassed GCA mean squares in all treatments and environments. Low GCA/SCA ratios (< 0.12), particularly under salinity stress, emphasized the major role of non-additive gene action for yield traits. This is particularly important for hybrid development, as it suggests strong hybrid vigor (heterosis) effects may be realized by exploiting specific cross combinations. Parental GCA effects indicated that P2 and p4 excelled as general combiners for both yield components across treatments, while p5 consistently had negative effects. This suggests that P2 and p4 are suitable donor lines for improving fruit yield under both control and saline conditions. Among the hybrids, crosses such as P1 × P3, P2 × P3, and P3 × P5 exhibited strong positive SCA effects for yield traits under both normal and saline environments. These combinations can be recommended as promising hybrid candidates for high fruit production in stressful and non-stressful environments. Some crosses, however, showed significant negative SCA effects under stress, highlighting the importance of careful parental selection for target environments. General combining ability (GCA) analysis revealed highly significant differences among parental genotypes for all traits. Positive and significant GCA effects were observed Edkawy and LA1673, for number of fruits per plant and for average fruit weight and total yield per plant in Castle Rock and Super Marmand. This suggests that these parents possess favorable additive genes for these traits, supporting their use in breeding programs for salinity tolerance and improved yield (Hassan, 2010 and Khalf-Allah et al., 2005). Specific combining ability (SCA) effects showed that certain crosses such as Castle Rock × SuperMarmand and Castle Rock × LA1673 had positive and significant effects for total yield per plant. The cross while Castle Rock × LA1963 had the highest average fruit weight. These results highlight the potential of specific hybrid combinations to improve marketable and adaptive traits under saline conditions (Hassan, 2010; Pratta and Picardi, 2003 and Wahb-Allah, M.A. (2008) Fruit Yield per Plant.

Table 1. Mean squares for general combining ability (GCA) and specific combining ability (SCA) for studied chemical content characteristics (total chlorophyll content and proline content in leaves) of tomato plants grown in greenhouses in the season (2023/2024) under saline conditions.

SOURCE	DF	Total chlorophyll content				Proline content/leaves			
Treatments		Control	T1	T2	T3	Control	T1	T2	T3
GCA	4	7.8135	8.2362	7.8627	5.2418	0.0076**	0.3657	0.0128**	0.0147**
SCA	10	18.9084	19.4321	18.6263	19.4854	0.0199**	0.8202	0.0374**	0.0437**
error	28	0.2671	0.2293	0.175	0.0695	0.0032	0.5961	0.0048	0.0012
RATIO BET GCA & SCA		0.0578	0.0596	0.0595	0.0381	0.0371	-0.146	0.0351	0.0481

Control, T1, T2 and T3 mean that values salinity levels =500, 4000, 6000, and 8000 ppm respectively.

Table 2. Mean squares for general combining ability (GCA) and specific combining ability (SCA) for studied chemical Content characteristics (Na^+/K^+ ratio and ascorbic acid content) of tomato plants grown in greenhouses in the season (2023/2024) under saline conditions.

SOURCE	DF	Na+/K+ ratio/leaves				Ascorbic acid content			
		Control	T1	T2	T3	Control	T1	T2	T3
GCA	4	0.0003**	0.0025**	0.0061**	0.0092**	**4.0944**	0.7787	0.9905	1.001*
SCA	10	0.0006**	0.0179**	0.0303**	0.0395**	**3.9841**	2.7577	3.5478	5.6079*
error	28	0.002	0.0007	0.0004	0.001	**0.3389**	0.0562	0.0594	0.0221
RATIO BET GCA & SCA		0.0704	0.0152	0.0271	0.0333	**0.1472**	0.0382	0.0381	0.025

GCA = General combining ability
SCA = Specific combining ability

Table 3. Mean squares for general combining ability (GCA) and specific combining ability (SCA) for studied yield components characteristics of tomato plants grown in green houses in the season (2023/2024) under saline conditions.

SOURCE	DF	Total No. fruit yield /plant				Total Fruits Weight Yield /Plant			
Treatments		Control	T1	T2	T3	Control	T1	T2	T3
GCA	4	309.6313	297.457	150.7024	33.9715	7.8402	7.0756	3.0954	0.6067*
SCA	10	432.7432	360.0113	253.012	202.3356	11.523	8.2479	5.119	3.6249*
error	28	34.3275	44.0277	21.2339	1.8699	0.6493	0.6973	0.3149	0.034
RATIO BET GCA & SCA		0.0987	0.1146	0.0798	0.0229	0.0945	0.1207	0.0827	0.0228

GCA = General combining ability
SCA = Specific combining ability

Table 4. Estimates of general and specific combining ability effects for studied chemical Content (total chlorophyll content and proline content in leaves) in the parents and F1 genotypes in tomato plants grown in greenhouse in the 2023\24 seasons under saline conditions.

Characteristics	total chlorophyll content				Proline content			
Genotypes	**Control**	**T1**	**T2**	**T3**	**Control**	**T1**	**T2**	**T3**
Parents				**GCA EFFECTS**				
p1	-0.57 **	-0.56 **	-0.45 **	-0.46 **	0.01 ns	-0.17 ns	0.01 ns	0.01 **
p2	0.95 **	0.96 **	0.93 **	0.86 **	-0.05 *	0.19 ns	-0.07 **	-0.07 **
p3	-0.92 **	-0.88 **	-0.87 **	-0.53 **	-0.01 ns	-0.18 ns	-0.01 ns	0.01 **
p4	1.33 **	1.38 **	1.33 **	1.00 **	0.03 ns	-0.14 ns	0.03 ns	-0.01 **
p5	-0.79 **	-0.89 **	-0.95 **	-0.87 **	0.02 ns	0.30 ns	0.04 ns	0.06 **
HYBRIDS				**SCA EFFECTS**				
P1 X P2	2.21 **	2.23 **	2.15 **	2.23 **	0.02 ns	-0.29 ns	-0.00 ns	-0.00 ns
P1 X P3	4.85 **	4.84 **	4.68 **	4.69 **	-0.12 **	-0.01 ns	-0.15 **	-0.17 **
P1 X P4	1.10 **	1.11 **	0.98 **	1.23 **	0.03 ns	0.25 ns	0.10 **	0.14 **
P1 X P5	2.51 **	2.61 **	2.46 **	2.40 **	-0.05 *	-0.30 ns	-0.01 ns	-0.03 **
P2 X P3	4.83 **	4.86 **	4.80 **	4.43 **	0.23 **	0.03 ns	0.32 **	0.30 **
P2 X P4	0.08 ns	0.09 ns	0.10 ns	0.41 **	-0.11 **	-0.51 ns	-0.22 **	-0.19 **
P2 X P5	-0.30 ns	-0.13 ns	-0.12 ns	-0.22 ns	0.10 **	2.45 **	0.16 **	0.14 **
P3 X P4	0.96 **	0.90 **	0.89 **	0.80 **	-0.05 *	0.07 ns	-0.08 *	-0.06 **
P3 X P5	4.40 **	4.54 **	4.57 **	5.17 **	0.16 **	-0.11 ns	0.18 **	0.27 **
P4 X P5	0.12 ns	0.15 ns	0.17 ns	0.35 **	0.12 **	-0.12 ns	0.17 **	0.19 **
GCA(j)	0.1747	0.1619	0.1414	0.0891	0.0192	0.261	0.0235	0.0003
SCA (ii)	0.4511	0.418	0.3652	0.2301	0.0497	0.6739	0.0606	0.0008
SCA (ij)	0.2256	0.209	0.1826	0.1151	0.0248	0.337	0.0303	0.0004

P1= Edkawy, P2 = Castle Rock, P3= CLN2498E, P4= Super Marmand, P5 = Super Strain B.

Table 5. Estimates of general and specific combining ability effects for studied chemical Content characteristics (Na^+/K^+ ratio and ascorbic acid content) in the parents and F1 genotypes in tomato plants grown in greenhouse in the 2023\24 seasons under saline conditions.

Characteristics	Na^+/K^+ ratio				Ascorbic acid content			
Genotypes	**Control**	**T1**	**T2**	**T3**	**Control**	**T1**	**T2**	**T3**
Parents		**GCA EFFECTS**				**GCA EFFECTS**		
p1	0.00 ns	0.01 ns	-0.01 ns	0.01 **	0.69 **	-0.29 **	-0.32 **	-0.40 **
p2	-0.00 *	-0.00 ns	-0.00 ns	-0.01 **	0.46 *	-0.03 ns	-0.00 ns	0.03 ns
p3	0.01 **	0.02 *	0.04 **	0.05 **	0.22 ns	-0.20 *	-0.30 **	-0.28 **
p4	-0.01 **	-0.02 *	-0.04 **	-0.05 **	-0.11 ns	0.56 **	0.61 **	0.57 **
p5	0.00 ns	-0.01 ns	0.02 *	-0.00 **	-1.26 **	-0.04 ns	0.00 ns	0.09 ns
HYBRIDS		**SCA EFFECTS**				**SCA EFFECTS**		
P1 X P2	-0.02 **	-0.05 **	-0.07 **	-0.10 **	3.60 **	1.10 **	1.20 **	1.30 **
P1 X P3	0.00 ns	-0.02 ns	-0.06 **	-0.06 **	-1.26 **	1.73 **	2.00 **	2.39 **
P1 X P4	0.01 **	-0.07 **	-0.08 **	-0.11 **	-1.90 **	-0.23 *	-0.18 ns	0.04 ns
P1 X P5	-0.01 **	-0.14 **	-0.19 **	-0.20 **	1.16 **	0.80 **	0.96 **	1.52 **
P2 X P3	-0.02 **	-0.21 **	-0.26 **	-0.29 **	-0.10 ns	1.97 **	2.18 **	2.45 **
P2 X P4	0.03 **	0.09 **	0.11 **	0.16 **	0.23 ns	0.51 **	0.50 **	0.90 **
P2 X P5	0.01 **	-0.02 ns	-0.04 **	-0.03 **	1.39 **	-0.19 ns	-0.12 ns	-0.19 **
P3 X P4	-0.03 **	-0.09 **	-0.08 **	-0.10 **	0.47 ns	1.08 **	1.34 **	1.65 **
P3 X P5	-0.02 **	-0.02 ns	0.01 ns	-0.05 **	0.62 *	0.14 ns	0.25 *	0.66 **
P4 X P5	-0.03 **	-0.10 **	-0.16 **	-0.15 **	1.95 **	1.48 **	1.50 **	1.81 **
GCA(j)	0.0017	0.0086	0.0067	0.0001	0.1968	0.0801	0.0824	0.0502
SCA(ii)	0.0043	0.0223	0.0174	0.0003	0.5081	0.2069	0.2127	0.1297
SCA(ij)	0.0022	0.0111	0.0087	0.0001	0.2541	0.1034	0.1064	0.0648

Table 6. Estimates of general and specific combining ability effects for studied yield components Characteristics in the parents and F1 genotypes in tomato plants grown in greenhouse in the 2023\24 season under saline conditions.

Characteristics	Total No Fruits Yield /Plant				Total Fruits Weight Yield /Plant			
Genotypes	Control	T1	T2	T3	Control	T1	T2	T3
Parents	GCA EFFECTS							
p1	-5.14 *	-3.88 ns	-2.44 ns	-1.36 **	-0.70 *	-0.37 ns	-0.20 ns	-0.04 ns
p2	5.35 *	4.36 ns	3.14 ns	2.28 **	0.85 **	0.79 **	0.51 *	0.28 **
p3	-3.05 ns	-2.86 ns	-1.56 ns	0.44 ns	-0.42 ns	-0.40 ns	-0.23 ns	0.03 ns
p4	8.79 **	9.10 **	6.24 **	1.68 **	1.37 **	1.24 **	0.80 **	0.20 **
p5	-5.95 **	-6.71 **	-5.38 **	-3.06 **	-1.10 **	-1.26 **	-0.88 **	-0.47 **
HYBRIDS	SCA EFFECTS							
P1 X P2	14.57 **	14.59 **	12.10 **	9.09 **	2.32 **	2.06 **	1.35 **	0.86 **
P1 X P3	23.47 **	21.81 **	15.53 **	8.92 **	3.77 **	3.19 **	2.31 **	1.48 **
P1 X P4	6.70 *	5.29 ns	6.80 **	8.85 **	1.22 **	0.97 *	1.13 **	1.41 **
P1 X P5	3.03 ns	4.66 ns	2.01 ns	-1.78 **	0.38 ns	1.03 **	0.49 ns	-0.23 **
P2 X P3	12.48 **	12.57 **	8.21 **	2.29 **	2.27 **	2.18 **	1.57 **	0.75 **
P2 X P4	5.41 *	6.11 *	8.15 **	11.55 **	0.96 *	1.32 **	1.47 **	1.94 **
P2 X P5	0.38 ns	4.42 ns	5.03 *	3.79 **	0.55 ns	0.59 ns	0.70 **	0.54 **
P3 X P4	7.01 *	6.43 *	5.04 *	4.52 **	1.62 **	1.10 **	0.55 *	-0.09 ns
P3 X P5	28.75 **	20.94 **	19.93 **	23.22 **	4.21 **	2.83 **	2.50 **	2.86 **
P4 X P5	-1.06 ns	0.68 ns	0.93 ns	1.39 *	-0.65 ns	-0.74 ns	-0.14 ns	-0.08 ns
GCA(j)	1.9807	2.2432	1.5578	0.4623	0.2724	0.2823	0.1897	0.0623
SCA (ii)	5.1141	5.7918	4.0222	1.1936	0.7033	0.7289	0.4898	0.1609
SCA (ij)	2.5571	2.8959	2.0111	0.5968	0.3517	0.3644	0.2449	0.0804

4. Discussion

The mechanism of action and interaction of General Combining Ability (GCA) and Specific Combining Ability (SCA) in plant breeding,

The genetic basis governing trait inheritance and expression in response to environmental stressors is reflected in the mechanism of action and interaction of General Combining Ability (GCA) and Specific Combining Ability (SCA) in plant breeding, especially in tomatoes grown in saline conditions.

The average effects of individual genes passed down from parents to children are known as additive genetic effects, or GCA. The parental lines' general capacity to consistently contribute advantageous alleles across crosses is reflected in these effects, which are comparatively stable. It is mostly linked to additive gene action, which can be gradually improved through selection (Sprague and Tatum, 1942; Xu, 2010). Strong additive genes that enhance these traits independent of the mating partner are indicated, for instance, by a parent with high positive GCA effects for traits like chlorophyll content or yield under salinity. SCA, on the other hand, takes into consideration non-additive genetic effects, such as dominance, epistasis, and gene interactions specific to a given hybrid combination. These effects, which are impacted by the genetic interaction between two parents, reflect departures from the prediction based on parental GCA. Heterosis (hybrid vigor) and particular cross combinations that perform better or worse than average parental contributions are captured by SCA (Reif et al., 2007; Amegbor et al., 2023). Because stress conditions can change gene expression and the magnitude of both additive and non-additive effects, the interaction between these genetic components and the environment (such as different salinity levels) is crucial. Salinity affects the usefulness of parents and hybrids, according to significant GCA × environment and SCA × environment interactions. This highlights the necessity of environment-specific breeding techniques. Certain crosses, for example, might only exhibit high SCA when exposed to salt stress, suggesting advantageous epistatic interactions that enhance tolerance (El-Shaarawy, 2010; Saeed et al., 2011). Finding parents with strong GCA effects for salt-responsive traits (such as proline accumulation, chlorophyll content, and Na/K balance) in tomato salt tolerance breeding guarantees the stable transfer of adaptive genes. In the meantime, choosing hybrids with notable positive SCA effects can take advantage of non-additive interactions to improve yield and salt tolerance in difficult circumstances (Javed et al., 2022; A Saeed et al., 2011).The genetic mechanism therefore emphasizes a two-pronged approach to maximize tomato crop productivity and salt tolerance concentrating on parents with superior additive gene effects while also taking advantage of particular hybrid combinations that show beneficial non-additive interactions.

5. Conclusion

The combined analysis across all traits confirms that non-additive gene action, dominance and epistasis, plays a greater role than additive effects in determining chemical content (chlorophyll, proline, Na^+/K^+ ratio, and ascorbic acid) and yield-related traits under both normal and saline conditions. Superior parents such as P4 (for chlorophyll, Na^+/K^+ ratio, ascorbic acid, and yield) and P2 (for yield) should be incorporated into breeding programs as donors of favorable alleles. At the same time, hybrids like P1×P3, P2×P3, and P3×P5 should be prioritized for commercial evaluation to exploit their high SCA and heterotic potential

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References

Amegbor, I.K.; van Biljon, A.; Shargie, N.G.; Tarekegne, A.; and Labuschagne, M.T. (2023). Combining ability estimates for quality and non-quality traits. Frontiers in Sustainable Food Systems, 50(2), 137–143.

Baker, R.J. (1978). Issues in diallel analysis. Crop Sciences. 18, 533–536.

Bates L.S; Waldren R.P.; and Teare I.D. (1973). Rapid determination of free proline for water-stress studies. Plant Soil, 39, 205–207. https://doi.org/10.1007/BF00018060

Cox, H.E. and Pearson, D. (1962). The Chemical Analysis of Foods. Chemical Publishing Co., Inc. New York.PP 136-144.

Cuartero, J.; Bolarin, M.C.; Asins, M.J.; Moreno, V. (2006). Increasing salt tolerance in the tomato. Journal of Experimental Botany, 57(5), 1045–1058.

Evenhuis, H.M. and de Waard, P.W.F. (1980) Principles and practices in plant analysis. FAO Soils Bulletin No. 38/2.

El-Shaarawy, G. A. (2010). General and specific combining ability studies. Journal of Plant Breeding.

FAOSTAT Database. (2011). world production of tomato. http://faostat.fao.org/

FAOSTAT Database. (2023). world production of tomato. http://faostat.fao.org/

Griffing, B. (1956). Concept of general and specific combining ability in relation to diallel crossing system. Australian journal of biological sciences, 9: 463-493.

Hassan, A.I.A. (2010). Mean performance, heterosis and combining abilities of tomato crosses under saline conditions. Journal of Agricultural Chemistry and Biotechnology, 1(2), 81-92.

Hung, H.Y. and Holland, J.B. (2012). Diallel analysis of resistance to Fusarium ear rot and fumonisin contamination in maize. Crop Science, 52, 2173–2181.

Javed, M. F.; Ali, M.; Javed, M.A.; Anjum, S.A.; and Khan, M.S. (2022). Evaluation of General and Specific Combining Ability in Tomato. Asian Journal of Crop Science, 14(3), 123–134.

Khalf-Allah, A.M.; Helmy, E.M. S.; Abdel-Aal, Z.; and Wahb-Allah, M.A. (2005). Estimates of combining abilities, heterosis and heritability of some important characters of tomato (*Lycopersicon esculentum* Mill). Alexandria Journal of Agricultural Sciences, 50(2), 137-143.

Liu, Z.; Jiang, J.; Ren, A.; Xu, X.; Zhang, H.; Zhao, T.; Jiang, X.; Sun, Y.; Li, J.; and Yang, H. (2021). Heterosis and combining ability analysis of fruit yield, early maturity, and quality in tomato. Agronomy, 11(4), 807.

Marquard, R.D. and Timpton, J.L. (1987). Relationship between extractable chlorophyll and an in situ method to estimate leaf green. Horticulture Sciences, 22, 1327.

Pratta, G.R. and Picardi, L.A. (2003). Diallel analysis of production traits among domestic, exotic and mutant germplasms of Lycopersicon. Genetics and Molecular Research, 2(2), 206-213.

Reif, J.C.; Gumpert, F.-M.; Fischer, S.; and Melchinger, A.E. (2007). Impact of interpopulation divergence on additive and dominance variance in hybrid populations, Genetics, 176(3), 1931–1934.

Saeed, A.; Shahid, M.Q.; Anjum, S.A.; Khan, A.A.; Shakeel, A.; Saleem, M.F.; and Saeed, N. (2011). Genetic analysis of NaCl tolerance in tomato. Genetics and Molecular Research, 10(3), 1754–177.

Shabala, S. and Cuin, T.A. (2008). Potassium transport and plant salt tolerance. Physiologia Plantarum, 133, 651–669.

Shalaby, T. A. (2013). Mode of gene action, heterosis and inbreeding depression for yield and its components in tomato (*Solanum lycopersicum* L.). Scientia Horticulturae, 164:540-543.

Solieman, T.H.I.; EL-Gabry, M.A.H.; and Abido, A.I. (2013). Heterosis, potence ratio and correlation of some important characters in tomato (*Solanum lycopersicum* L.). Scientia Horticulturae, 150, 25 – 30.

Sprague, G.F. and Tatum, L.A. (1942). General vs. specific combining ability in single crosses of corn. Journal of the American Society of Agronomy, 34(10), 923–932.

van Zelm, E.; Zhang, Y.; and Testerink, C. (2020). Salt tolerance mechanisms of plants. Annu. Rev. Plant Biology, 71, 403–433.

Wahb-Allah, M.A. (2008). A diallel analysis of yield and yield components of some tomato genotypes grown in arid conditions. Zagazig Journal of Agriculture Research, 35(1), 19-32.

Xu, S. (2010). Quantitative Genetics and Breeding. Elsevier, Amsterdam. pp. 1–368.