

Half diallel of F1 tomato hybrid and its double cross-compatibility

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Abstract. Farid M, Anhsori MF, Ridwan I, Dunga NE, Ermiyanti I. 2022. Half diallel of F1 tomato hybrid and its double cross-compatibility. *Biodiversitas* 23: 1813-1821. Breeding program for improvement of tomato fruit can be done through diallelic crosses genetic combinations. Therefore, genetic evaluation is needed to meet the breeding objective. This process can be combined with crosses between F1 to produce high diversity. However, evaluating the crosses' compatibility is required to increase the effectiveness of the assembly process. This study aimed to assess the half-diallel crosses of F1 tomatoes in the field and determine the most compatible pair cross combinations in forming double and three-way F1 populations. This study was carried out in the Experimental Farm of the Faculty of Agriculture, Hasanuddin University. The field evaluation was arranged in a randomized complete block design with ten genotypes, while the compatibility evaluation was carried out using 6 F1 half diallel as the parents. The results showed that the Mawar and Chung varieties were better parents in the crossings. Furthermore, the results showed that F1 K/M (the best yield component), M/C (the best TDS and Lycopene traits), and BC/K (the genotype has good traits of yield component, TDS and Lycopene) were the best single F1 crosses that could be inherited to the F2 generation. In contrast, F1 K/M and F1 K/C crosses were the best male and female parents, respectively. The recommended double-crosses include K/C/BC/M, and BC/C//K/M, while for the F1 unbalanced three-way cross was K/C//K/M.

Keywords: Compatible ability, diallel mating, double-cross, hybrid tomato, *Solanum lycopersicum*

Abbreviations: BC: Blackcherry, C: Chung, K: Karina, M: Rose, FD: fruit diameter, FL: fruit length, TDS: total dissolved solids, FW: fruit weight, L: lycopene, NBP: number of bunches per plant, NFB: number of flowers per bunch, NFpB: number of fruits per bunch, SD: stem diameter

INTRODUCTION

Tomato (*Lycopersicon esculentum* Mill) is one of the food products that are rich in natural antioxidants. It has good antioxidant content, specifically lycopene, which improves the immunity of the human body (Elbadrawy and Sello 2016; Fraser et al. 2020; Przybylska 2020). The antioxidant content in tomatoes has a variety of health benefits and diverse nutritional content such as fiber, carbohydrates, vitamins, minerals, and protein and fat (Raiola et al. 2015; Leiva-Brondo et al. 2016; Campestrini et al. 2019). These benefits have made the fruits highly demanded by the public (Fentik 2017; Chaudhary et al. 2019). However, the growth of tomatoes production is considered slow. According to the statistics of Indonesia (2021), the average growth increase of this fruit is 5.13%. Therefore, developing the productivity and quality of tomatoes in line with the population rate is one of the keys to stabilizing the rate of production and demand.

One of the main problems of tomato cultivation in Indonesia is the lack of high-yielding superior varieties with good fruit quality and resistance to pests and diseases (Suyadi and Rosfiansyah 2017; Schreinemachers et al. 2018; Piosik et al. 2019; Oliveira et al. 2020; Afifah et al. 2021). Therefore, efforts to obtain superior varieties need to be carried out, both with conventional and breeding

methods such as crosses (Holme et al. 2019; Campanelli et al. 2019; Avdikos et al. 2021), mutation breeding, and genetic engineering (Ayanan et al. 2019; Chaudhary et al. 2019; Cappetta et al. 2020; Afifah et al. 2021; Breitel et al. 2021; Salava et al. 2021). In addition, due to the various benefits of tomatoes, more improvement needs to be carried out on the plant in terms of productivity, fruit quality, resistance to plant pest organisms, and tolerance to various environmental stresses (Acquaah 2012). Therefore, the plant crosses are required to obtain adaptive and high-quality tomatoes that meet consumers' preferences. Furthermore, according to Mustafa et al. (2019), the assembly of different varieties through crossing can induce the dominant and overdominant gene action based on the desired traits. This gene action would be able to create lines that are better than their parents and be effective in improving the crop.

The crossing methods strongly influence the formation of tomato diversity. Examples include single, double, three-way, multiple, backcrosses, and diallel mating. Diallel mating is a crossing technique that creates a high diversity of crosses (Olfati et al. 2012; Zeinab and Helal 2014; Murtadha et al. 2018; Mat et al. 2020). This high diversity serves as an equal opportunity for each parent to be crossed with each other; hence, the number of possible crosses can be the combinatorics of all the parents involved (Olfati et

al. 2012; Bouchetat and Aissat 2019; Mat et al. 2020). In addition, this analysis can be used to explore genetic parameters in detail, both on genetic diversity, heritability, gene action, and combining ability (Syukur et al. 2010; Ghareeb and Fares. 2016; Ene et al. 2018; Zongo et al. 2019). These advantages have made this method commonly used by many breeders (Syukur et al. 2010; Bahari et al. 2011; Murtadha et al. 2018; Zongo et al. 2019; Mat et al. 2020). However, diallel crosses do not necessarily involve all possible combinations (full diallel). Some studies also use the concept of half diallel because it involves the use of several combinations of pure line parents in the absence of their reciprocals (Olfati et al. 2012; Ene et al. 2018; Boyaci et al. 2020; Dianga et al. 2020; Datta et al. 2021). Although this combination is not as much as in full diallel crosses, this method is quite effective for a small number of parents and focuses on the nature of cross interactions that do not involve maternal effects (Singh and Chaudhary 1979; Olfati et al. 2012; Datta et al. 2021). This would help in minimizing the error effect of the coupling test. Based on Bdr et al. (2020), 6 F1 results from half diallel crosses from 4 parents (Black Cherry, Karina, Mawar, and Chung) need to be evaluated and increased for their diversity. The increase in the diversity of the F1 will be correlated with the chances of superior offspring formation to meet the breeder's expectations. Furthermore, this can be performed by double-crossing between F1 hybrids.

Double crosses can create greater population diversity than single cross F1 (Acquaah 2012; Muthoni and Shimelis 2020; Joshi and Gautam 2021). This concept is crucial in producing adaptive tomato varieties that suit consumer expectations (Campanelli et al. 2019; Matos et al. 2021). These double-cross from the half-diallel single cross can be combined with diallel mating, and this concept has been reported by Matos et al. (2021). Furthermore, the combination from half diallel can form F1 double and unbalanced three-way crosses. Both population concepts can increase the opportunity to develop tomato genotypes with high productivity and good fruit quality. Furthermore, the combination of these crosses is also determined by their compatibility (Deprá et al. 2014; Farid et al. 2021). However, because tomato plants are self-pollinating, the success of crosses is relatively more difficult (Deprá et al. 2014; Piosik et al. 2019). Therefore, it is also important to observe the cross-compatibility to increase the effectiveness of crosses between F1. This study aimed to evaluate the half-diallel crosses of F1 tomatoes in the field based on agronomy and lycopene characters and determine the best compatible pair crosses to form either double or unbalanced three-way F1 population.

MATERIALS AND METHODS

The study was carried out in the Experimental Farm of the Faculty of Agriculture, Hasanuddin University, Tamalanrea District, Makassar City, South Sulawesi, Indonesia from March to November 2021. The location is 22.4 m above sea level with an average minimum and maximum temperature of 24°C and 32°C, respectively.

Two experiments were conducted simultaneously on different farm sites with different methods.

F1 hybrid evaluation

This first experiment evaluated the diversity of tomato F1 hybrids using a randomized complete block design (RCBD) with three replications. In addition, ten genotypes consisting of 6 combinations of F1 half diallel crosses were used to focus on the productivity and lycopene traits (Chung x Mawar, Karina x Mawar, Black Cherry x Mawar, Karina x Chung, Black Cherry x Chung, Black Cherry x Karina) of the four parents, namely, Karina (oval fruit shape and good productivity), Mawar (wavy fruit shape and good productivity), Black Cherry (round fruit shape and high lycopene) and Chung (little round fruit and high lycopene). Therefore, there were 30 experimental plot units with ten plant samples based on this experiment.

Double cross-compatibility trial

The double-cross and compatibility experiments were carried out between F1 single crosses with the concept of a diallelic cross, using six parents, each of which had five plants, bringing 30 crosses. The crossing process for each cross combination was carried out 30 times to produce 900 crosses units.

Study implementation

Seeding was conducted previously in a GreenHouse to control the seedlings easily. The planting medium used was a ratio of 1:1 roasted husk and compost. Before planting, the planting medium was irrigated to field capacity level and then applied with Furadan to avoid interference or pest attacks. At 7 DAS, they were given ABmix solution with a dose of 5 mL per Liter of water around the plant roots. The seedlings were then transplanted into pots or polybags about 14 days after sowing (DAS).

Transplanting was conducted by transferring tomato seedlings about two to three weeks after planting (WAP) to the bed. The beds were made with a width of 80 cm and a length of 2.5 m with a distance of 30 cm. The beds were covered with black silver plastic mulch, and the planting holes were made by perforating the plastic using a 10 cm diameter can. The spacing used was 60 cm and 80 cm in and between rows. Furthermore, the spacing affects the humidity level around the plant, the level of soil nutrients used, the level of pathogen development, such as pests, fungi, viruses, and bacteria, and the intensity of sunlight reception.

Plant maintenance included watering, replanting, fertilizing, pruning, weeding, and controlling pests and diseases. Watering was performed twice a day in the morning and evening using a watering can or sprinklers. Unhealthy seedlings we replaced with new healthy ones. Fertilization was carried out one WAP, while the next was given once a week. Fertilization was carried out using NPK Mutiara fertilizer (16:16:16) at 250 mL application solution per plant with 10 g L⁻¹ of water. At the next fertilization KNO₃ at a dose of 5 g L⁻¹ was added. In addition, NPK Mutiara was given in the form of a solution applied around the plant roots during the reproductive phase, while

Gandasil B (6% Nitrogen, 20% Phosphate, 30% Potassium and 3% Magnesium) was used during the generative phase. Pruning was conducted at least once a week to remove the initial or small shoots on the lower stem and on other shoots to direct the growth of the tomatoes to the main stem. In addition, weeding was carried out manually.

Prevention and control of pests and plant diseases were carried out once a week using a mixture of Curacron 500 E and fungicide Antracol 70 WP C with a concentration of 2 cc L⁻¹ and 2 g L⁻¹ of water. This application was also combined with Dhitane M-45 WP and a concentration of 2 g L⁻¹ of water in place of the fungicide Antracol 70 WP to get more effective control. Pesticides were applied by spraying the plant surface and harvesting twice a week. The fruits ready for harvest were those that had a reddish-yellow color.

Tomato plant crossings processes

Crosses were conducted using all possible combinations among a group of parent materials. The crossings were carried out as follows. Preparation: This process includes preparing the equipment needed, crossing the tomatoes, knowing the morphology and phenology of the plants, and selecting the best female and male elders to be crossed. Castration is cleaning or removing plant parts around the flowers to be emasculated from dirt, insects, unused flower buds, other plant organs that interfere with crosses, and the disposal of crowns and petals on tomato plants. Emasculation is removing the male genitalia (stamen) on the female parent to be crossed. The emasculation method used in this study of tomato crosses was the clipping or tweezers. Pollen collection involves taking pollen from previously selected male parents. The tool used to take pollen was a needle or tweezers. Pollination is the process of putting pollen that has been taken from the male parent to the stigma of the female parent. Isolation, confinement is the activity of covering the flowers of the female parent crossed using a cover or others to avoid un-wanted crosses/pollination. Finally, labeling was conducted by providing information on the breeder's name and parent of the cross and the date to facilitate the identification of the cross fruit.

Observation

Quantitative parameters of F1

The quantitative characters observed was based on Ermiyanti et al. (2021), namely, plant height (cm), days to flowering (DF) and harvesting (DH), stem diameter (cm), number of bunches per plant (bunch), number of flowers per bunches (flowers), number of fruits per bunch (fruit), fruit length (cm) and diameter (cm), total dissolved solids (brix), fruit weight (g), fresh fruit yield (ton ha⁻¹), and lycopene content. The analysis of lycopene content was based on Bdr et al. (2020).

F1 double cross-compatibility parameters

The quantitative characters observed were fruit crossing success per plant, the fruit diameter (cm), fruit flesh thickness (cm), fruit length (cm), total dissolved solids

(brix), as well as average weight and number of seeds per fruit.

Data analysis

The field evaluation data were subjected to analysis of variance (ANOVA) using Griffing method II (Sigh and Chaudary 1979). The Hybrid with a significant effect was further evaluated for both general and specific combining ability. The GCA LSD was commonly compared among the parents using SE GCA. For SCA, there were two methods. If the hybrid was compared with the same female parent, LSD used SE (Sii-Sij).

Meanwhile, if the hybrid was compared with another female, LSD used SE (Sii-Sik). Then, if the hybrid was compared with another female parent, LSD used SE (Sii-Sij). The cross-pollination full diallel was analyzed with success percentage. Furthermore, its fruit characters of result crossing were analyzed with ANOVA through Griffing method I (Sigh and Chaudary 1979). The Griffing ANOVA used Software Pbttools 1.4 from IRRI (Bartolome et al. 2014).

RESULTS AND DISCUSSION

ANOVA and genetic components

The interaction between parent 1 (P1) and parent 2 (P2) on tomato growth significantly affected all plant characters. General combining ability (GCA) significantly affected days to flowering, days to harvesting, number of bunches per plant, total dissolved solids, number of flowers per bunch, fruit diameter, total dissolved solids, and yield. Meanwhile, specific combining ability (SCA) had a highly significant effect on almost all observed characters, except the days to harvest (Tables 1 and 2).

The days to harvesting, stem diameter, number of bunches per plant, fruit diameter, total dissolved solids, and yield showed an A/D ratio of >1.0. Meanwhile, the A/D ratio of <1 was found on plant height, DH, number of flowers and fruits per bunch, length, lycopene, and fruit weight. All tomato growth characters with broad-sense heritability values (H²) were high. On the other hand, almost all the characters had a narrow sense heritability value (h²) of < 0.5, except DH (0.72), total dissolved solids (0.85), and yield (0.6).

GCA and SCA of the tomato growth characters

The GCA and SCA of several significantly affected growth characters are presented in Tables 3 and 4. The lowest GCA of DF was shown by the Cung parents (-7.84), while Blackcerry had the highest score (7.21). Based on the DH parameter, the lowest GCA value was found in the Cung parents (-2.01) and not significantly different from the Mawar variety (-1.92). Furthermore, Karina's parents had the highest GCA value of 2.03, but it was not substantially different from Blackcerry (1.90). The best GCA value was found in Cung parents (2.12) and not significantly different from Mawar (1.12) for the number of bunches per plant. The Mawar parents had the highest GCA of fruit diameter and yield value of 0.54 and 0.87,

respectively. In addition, for total dissolved solids, the highest GCA value was from Blackcherry (1.18) and not significantly different from Karina (0.04).

The results of the specific combining ability are shown in Tables 3 and 4. Based on characters that SCA only influenced, the best hybrid genotype SCA values on plant height, stem diameter, number of flowers, fruit length, fruit weight, lycopene characters were BC/K (15.53), K/M (0.23), M/C hybrid (3.10), K/M hybrid (1.59), K/M hybrid (13.29), and BC/K (5.03), respectively. All these hybrids have significant differences with the Blackcherry variety. Based on characters that have significance in SCA and GCA, the best hybrid genotype SCA values on the number of fruits per bunch, fruit diameter, total dissolved solids content, and yield are M/C hybrid (1.37), BC/C hybrid (0.95), K/C (0.42), and K/M hybrid (4.40), respectively. All these hybrids also have significant differences with the Blackcherry variety. On the other hand, the lowest SCA of DF trait was observed on BC/M (-3.95).

Compatibility analysis of double cross among F1 tomato half diallel

The results of the tomato crossing compatibility analysis showed that the F1 K/C hybrid was the best female

parent (35.00%), while K/M hybrid was the best male parent (31.33%) (Table 5). K/C//BC/K and K/C//BC/C double-cross hybrids showed the high percentage level of compatibility of multiple crosses with a percentage of 43.33% and 40%, respectively. In addition, the lowest percentage level of cross-compatibility was shown by double-cross hybrids BC/C//K/C, BC/C//M/C, and K/M//BC/M, each with 13.33% level of compatibility (Table 5).

The GCA of double cross based on fruit characters

The results of GCA analysis for fruit diameter, length, thickness, weight and cavity, total dissolved solids, and the number of seeds were presented in Table 6. The best GCA values for the characters of fruit diameter and length, total dissolved solids, were shown by, respectively, F1 K/C (3.75), F1 K/M (7.13), F1 BC/C (0.53), and BC/M (1.14). As for the fruit thickness, cavities, and last character, the best GCA values were shown by K/M (3.63), BC/K (0.12), and F1 K/C (6.63); however, it was not significantly different from that of K/C (3.38), M/C hybrids (0.10), and K/M hybrids (5.88).

Table 1. Results of ANOVA and genetic components of vegetative and inflorescence characters

SV	PH	DF	DH	SD	NBP	NFB
P1:P2	233.02**	347.72**	37.00**	2.24**	38.19**	13.34**
Residual	67.46	10.15	4.97	0.29	2.88	2.11
GCA	37.85 ^{ns}	241.60**	30.84**	1.48 ^{ns}	24.66**	6.85 ^{ns}
SCA	97.59**	53.06**	3.08 ^{ns}	0.38**	6.77**	3.25**
Error	21.07	3.33	1.66	0.09	0.96	0.70
Variance of additives effect (A)	0.00	125.69	18.50	0.36	5.97	1.20
Variance of dominant effect (D)	76.52	198.91	5.70	0.30	5.80	2.54
Ratio of A/D	0.00	0.63	3.25	1.20	1.03	0.47
h ² (Broad Sense)	0.78	0.99	0.94	0.88	0.92	0.84
h ² (Narrow Sense)	0.00	0.38	0.72	0.48	0.47	0.27

Note: **Highly significant at 1% level ($P < 0.01$), *Significantly influential at 5% level ($0.01 \leq P < 0.05$), ns: Not significant ($P \geq 0.05$), SV: sources of variation, PH: plant height PH, DF: days to flowering, DH: days to harvest, SD: stem diameter, NBP: number of bunches per plant, NFB: number of flowers per bunch

Table 2. Results of ANOVA and genetic components of fruit and yield characters

SV	NFpB	FD	FL	TDS	FW	Yield	L
P1:P2	3.54**	2.25**	5.04**	4.80**	378.04**	313.99**	48.79**
Residual	0.33	0.29	0.16	0.10	1.22	0.45	1.56
GCA	1.29 ^{ns}	1.47**	3.03 ^{ns}	4.33**	155.40 ^{ns}	230.97**	15.97 ^{ns}
SCA	1.12**	0.39**	1.01**	0.23**	111.32**	41.51**	16.41**
Error	0.11	0.09	0.05	0.03	0.38	0.14	0.52
Variety of additives (A)	0.06	0.36	0.67	1.37	14.69	63.15	0.00
Dominant Variety (D)	1.01	0.30	0.96	0.20	110.95	41.37	15.89
Variety A/D	0.06	1.20	0.70	6.85	0.13	1.53	0.00
H2 (Broad Meaning)	0.91	0.88	0.97	0.98	1.00	1.00	0.97
h2 (Narrow Meaning)	0.05	0.48	0.40	0.85	0.12	0.60	0.00

Note: **Significantly influential at 1% level ($P < 0.01$); *Significantly influential at 5% level ($0.01 \leq P < 0.05$); ns: not significant ($P \geq 0.05$), SV: sources of variation, NFpB: number of fruits per bunch, FD: fruit diameter, FL: fruit length, TDS: total dissolved solids, FW: fruit weight, L: lycopene

Discussion

Evaluation of half diallel

ANOVA on the half diallelic showed a significant effect on all characters, indicating that the half diallelic concept was effective. The effectiveness of using the half diallelic mating design was also reported by Pandiarana et al. (2015); Kumar and Paliwal (2016); Kaushik and Dhaliwal (2018); and Vijeth et al. (2019) on tomatoes, Boyaci et al. (2020) and Datta et al. (2021) on eggplant, and Dianga et al. (2020) on rice. Based on these studies, an in-depth analysis of genetic parameters, namely heritability, gene action, and combining ability, can be determined.

Heritability is a commonly identified genetic parameter that describes the magnitude of the genetic diversity's proportion to phenotypic diversity (Acquaah 2012; Fikere et al. 2020; Barreto et al. 2021). Therefore, it has become one of the bases in determining the effectiveness of selecting and assessing a population (Munene et al. 2018; Parkes et al. 2020; Kaur et al. 2021). Specifically, the heritability approach is divided into two; the broad and narrow senses of heritability. The broad-sense approach indicates the general genetic influence of a population on the diversity of its phenotypic traits. Furthermore, the narrow-sense approach emphasizes the effect of inherited gamete diversity on the phenotypic diversity of a population (Acquaah 2012; Ogunniyan and Olakojo 2015; Mistry et al. 2016; Mawasid et al. 2019; Kumar and Srivastava 2021). Based on the results of this study, it was found that all characters had high broad-sense heritability. However, these high broad-sense heritabilities are not supported by the total dissolved solids and the yield that still showed high narrow-sense heritability. This indicates that the phenotype of the characters is dominated by its genetic influence and can be passed on to the next generation, specifically the total dissolved solids and yield. Evaluation of crosses based on the heritability of tomatoes was also reported by Amaefula et al. (2014), Mawasid et al. (2019), Florido-Bacallao et al. (2021), and Kumar and Srivastava (2021). Therefore, the assessment of crosses in this study was effective.

Gene action is one of the genetic parameters that determine the pattern of gene control for a trait and can also be used to provide information on the pattern and direction of selecting a cross method (Zeinab and Helal 2014; Mistry et al. 2016; Ene et al. 2018; Farooq et al. 2019; Zongo et al. 2019). In general, gene action is divided into additive and non-additive (Kaushik and Dhaliwal 2018; Farooq et al. 2019; Zongo et al. 2019; Dianga et al. 2020). The additive action of this gene is identical to the ability of inherited gametes to control a particular trait (Acquaah 2012; Zeinab and Helal 2014; Vijeth et al. 2019). Meanwhile, the non-additive gene action is identical to allele interactions, both within the same locus and between different loci, while controlling a trait (Acquaah 2012; Hakim and Suyanto 2017; Hivert et al. 2021). This can be in the form of dominance, over-dominance, and epistatic gene action (Acquaah 2012; Nugraha et al. 2016). According to Marwiyah et al. (2019), Dianga et al. (2020), and Datta et al. (2021), the determination of gene action can be carried out by ratios or comparisons of additive and

dominant diversity. A ratio of more than 1 indicates that the character is more dominated by additive gene action while a ratio of less than 1 shows that it is influenced by the dominant gene action. Based on this study, the number of characters controlled by additive gene action had relatively the same with non-additive gene action; therefore, genotypes with high GCA and SCA will have good progeny vigor when crossed with other genotypes with characters that are controlled by non-additive gene action. However, the determination of the concept of selection from this study can be directed towards its primary objective. When it's based on productivity, the selection pattern used will lead to the action of the additive gene. This has also been reported by Pandiarana et al. (2015), Kaushik and Dhaliwal (2018), and Vijeth et al. (2019). Furthermore, when the selection is focused on the lycopene trait, the pattern used will lead to the non-additive gene's action, which is in line with Pandiarana et al. (2015). Cross-examination is also required while identifying the pattern of gene action reflected while combining different parameters.

Combining ability is a parameter that describes the ability of a genotype when crossed with other genotypes (Zeinab and Helal 2014; Murtadha et al. 2018; Marwiyah et al. 2019). This is closely related to the pattern of gene action; therefore, it is divided into two types, namely GCA and SCA (Pandiarana et al. 2015; Ghareeb and Fares 2016; Kaushik and Dhaliwal 2018; Farooq et al. 2019; Vijeth et al. 2019). GCA is identical abilities for additive gene action, therefore, genotypes with high GCA tend to produce good progeny vigor after being crossed (Olfati et al. 2012; Pandiarana et al. 2015; Ene et al. 2018; Murtadha et al. 2018; Zongo et al. 2019; Boyaci et al. 2020; Dianga et al. 2020; Datta et al. 2021). This means that the development of this variety can be directed into pure-line or composite varieties and the formation of hybrids (Bahari et al. 2012; Bouchetat and Aissat 2019, Marwiyah et al. 2019). Based on this study, the genotype with high GCA in almost all characters was the Mawar variety, followed by Chung. This indicates that crosses further employed for the breeding process should have one parent consisting of the Mawar or Chung varieties. The cross with the highest SCA on production and lycopene characters was F1 K/M and F1 M/C. Meanwhile, the cross with SCA, which was quite good in both traits, was the BC/K cross. The results indicated that K/M and M/C crosses are highly recommended for breeding in the next generation. This refers to the recommended parental GCA value in this study.

The BC/K crosses can also be recommended for breeding because they had a fairly good SCA in both parents, but the GCA value was considered poor for productivity and lycopene traits. In general, an F1 cross will undergo segregation in the F2 generation, producing the expected recombinant characters (Cazzola et al. 2020; Mackay et al. 2021) for the BC/K lineage to produce the expected offspring in both characters. K/M and M/C crosses will also have less chance of producing round or oval fruit offspring than BC/K crosses. However, the older species of Blackchery (BC) and Karina (K) had round and

oval fruit shapes. Therefore, their offspring's chances of this kind of shape from this cross were high. Therefore, it was concluded that the BC/K cross can still be used in the lineage process.

Evaluation of double-cross compatibility between F1 half diallel

The results of double cross-compatibility were evaluated based on the female and male parents. This concept has also been reported by Bedinger et al. (2010), Zhang et al. (2019), and Farid et al. (2021) on crosses between tomato species, *Tagetes erecta* and *T. patula*, Farid et al. (2021) on crossing cocoa plants. The results of this study showed that F1 K/C became the best female

parent in the double-cross, while F1 K/M and F1 BC/K were the best male parents. Based on the F1, Elder Karina became the basis for forming the best F1 for double-crossing. These results indicate that the use of Karina is excellent in terms of cross-compatibility. F1 K/M cross had good potential with SCA productivity during field evaluation, suggesting that it can increase the potential for productivity in the inheritance process. However, further support is required for the fruit phenotype of this cross. This evaluation can be performed by looking at the potential of GCA based on the character of the F1 K/M cross.

Table 3. Value of GCA and SCA of vegetative and inflorescence characters

Parent	PH	DF	DH	SD	NBP	NFB
GCA						
BC	-1.87	7.21 ^k	1.90 ^k	-0.72	-0.81 ^l	-1.33
C	2.98	-7.84 ⁿ	-2.01 ^l	-0.44	2.12 ^k	1.11
K	-2.28	2.19 ^l	2.03 ^k	0.56	-2.44 ^m	-0.33
M	1.17	-1.56 ^m	-1.92 ^l	0.6	1.12 ^k	0.55
SCA						
BC/C	-4.73	4.33 ^b	-1.14	0.20 ^{abcd}	1.63	0.35
BC/K	15.53 ^{abd}	7.46 ^{abc}	0.48	-0.06 ^c	2.63 ^{ad}	1.14 ^{ad}
BC/M	-1.48	-3.95	-1.01	-0.55	-0.26	0.7
K/M	-5.55	7.46 ^{abc}	1.73	0.23 ^{abcd}	-3.41	-1.42
K/C	-9.4	1.52 ^c	2.41	-0.03 ^{abcd}	-1.52	-1.19
M/C	13.23 ^a	7.66 ^a	0.34	-0.65 ^d	3.26 ^a	3.10 ^a
SE (GCA)	5.56	2.21	1.56	0.29	1.19	1.01
SE (Sii-Sij)	12.45	4.95	3.49	0.67	2.66	2.28
SE (Sii-Sjk)	11.13	4.43	3.12	0.6	2.38	2.04

Note: BC: Blackcherry, C: Chung, K: Karina, M: Mawar. For GCA, the numbers followed by the same letter in the row (k, l, m, n) are significantly different in the 5% least significant difference (LSD) test. For SCA, numbers followed by letters differ significantly from their parents, BC: a; C: b; K: c; M: d. PH: plant height PH, DF: days to flowering, DH: days to harvest, SD: stem diameter, NBP: number of bunches per plant, NFB: number of flowers per bunch

Table 4. Value of GCA and SCA of vegetative and fruit and yield characters

Parent	NFpB	FD	FL	TDS	FW	Yield	L
GCA							
BC	-0.18	-0.62 ^m	-0.87	1.18 ^k	-5.79	-5.55 ^m	2.28
C	0.67	-0.12 ^l	-0.29	-0.71 ^l	-2.75	-1.22 ^l	-0.25
K	-0.1	0.21 ^l	0.52	0.04 ^k	4.04	-2.11 ^l	-1.6
M	-0.39	0.54 ^k	0.64	-0.51 ^l	4.51	8.87 ^k	-0.43
SCA							
BC/C	0.05	0.95 ^{abcd}	0.08 ^{ad}	-0.16	-0.18	0.92 ^{abcd}	1.73 ^{bc}
BC/K	-0.87	-0.55 ^c	0.07 ^{ad}	0.33 ^{abc}	-1.77	0.85 ^{abcd}	5.03 ^{abcd}
BC/M	-1.22	-0.14	-0.53	-0.87	-2.4	-4.75	2.64
K/M	0.19	0.43 ^a	1.59 ^{abcd}	-0.28	13.29 ^a	4.40 ^{abcd}	-2.65
K/C	-0.64	-0.20 ^d	0.30 ^{abcd}	0.42 ^{abc}	-14.15	-9.87 ^d	-2.74
M/C	1.37 ^a	-0.67 ^d	-1.24 ^d	0.22 ^{bc}	-9.91	-3.84 ^{ad}	4.36 ^{abcd}
S.E (GCA)	0.4	0.36	0.26	0.2	0.74	0.45	0.87
SE (Sii-Sij)	0.9	0.81	0.6	0.46	1.66	1.02	1.95
SE (Sii-Sjk)	0.8	0.72	0.53	0.41	1.49	0.92	1.75

Note: BC: Blackcherry, C: Chung, K: Karina, M: Mawar. For GCA, the numbers followed by the same letter in the row (k, l, m, n) are significantly different in the 5% LSD test. For SCA, numbers followed by letters differ significantly from their parents, BC: a, C: b, Karina: c, Mawar: d. NFpB: number of fruits per bunch, FD: fruit diameter, FL: fruit length, TDS: total dissolved solids, FW: fruit weight, L: lycopene

Table 5. The percentage value (%) of tomato crossing compatibility of the F1 hybrid double cross

ELDER F/M	BC/C	BC/K	BC/M	K/M	K/C	M/C	Female	Female (%)
BC/C	-	23.33	16.67	23.33	13.33	13.33	90.00	18.00
BC/K	20.00	-	16.67	26.67	16.67	26.67	106.67	21.33
BC/M	30.00	26.67	-	36.67	36.67	16.67	146.67	29.33
K/M	33.33	30.00	13.33	-	33.33	20.00	130.00	26.00
K/C	40.00	43.33	26.67	36.67	-	23.33	170.00	35.00
M/C	16.67	30.00	33.33	33.33	16.67	-	130.00	26.00
Male	140.00	153.33	106.67	156.67	116.67	100		
Male (%)	28	30.67	21.33	31.33	23.33	20		

Note: BC: Blackcherry, C: Chung, K: Karina, M: Rose; /: Cross single, F/M: female/male

Table 6. GCA value of fruit diameter (FD), fruit length (FL), fruit thickness (FT), fruit cavity (FC), total dissolved solids (TDS), fruit weight (FW), and the number of seeds (NS.)

Parent	FD	FL	FT.	FC	TDS	FW	NS
BC/C	-3.27 ^e	-2.80 ^e	-2.26 ^e	-0.22 ^b	0.53 ^a	-2.14 ^c	-0.36 ^b
BC/K	0.79 ^b	-0.40 ^{bcd}	0.99 ^b	0.12 ^a	0.34 ^b	-0.85 ^b	-2.03 ^d
BC/M	-0.31 ^{bcd}	-0.22 ^{bc}	-0.51 ^c	-0.01 ^{ab}	0.38 ^b	-0.95 ^b	1.14 ^a
K/C	3.75 ^a	6.37 ^b	3.38 ^a	-0.15 ^{ab}	-0.81 ^d	6.63 ^a	-1.90 ^{cd}
K/M	0.70 ^b	7.13 ^a	3.63 ^a	-0.38 ^c	-0.50 ^c	5.88 ^a	-3.13 ^e
M/C	-1.67 ^{de}	-3.26 ^e	-1.81 ^{cd}	0.10 ^a	-0.28 ^b	-2.53 ^c	-0.82 ^c

Note: BC: Blackcherry, C: Chung, K: Karina, M: Rose. The numbers followed by the same letter in the row (a, b, c, d, e) mean significantly different in the LSD test at 5% level

The results of the GCA evaluation showed that F1 K/C and F1 K/M had the best GCA values for all characters. This is in line with its potential compatibility as a parent of double-crossing. In general, this evaluation still involves the influence of the female parent. It was also found that the potential for fruit development of these crosses cannot be separated from the suitability of their male parents (Dung et al. 2021; Farid et al. 2021; Stasiak et al. 2021). As a result, crosses with F1 K/C and F1 K/M parents can increase the diversity of offspring in double-crosses and examples include K/C//BC/M, and BC/C//K/M. The K/C//K/M is an unbalanced three-way cross that is predicted to have high diversity. According to Vekariya et al. (2019), crosses with significant GCA values are expected to maximize opportunities for high genetic diversity in their offspring, specifically for the desired character. Therefore, double-crosses such as K/C//K/M, K/C//BC/M, and BC/C//K/M are expected to maximize the opportunities for diversity in F2 double cross progeny in terms of productivity and lycopene properties.

In conclusion, the tomato F1 half diallelic cross had high genetic diversity and good ability for almost all characters, specifically for total dissolved solids and yield. The non-additive gene action affected the lycopene, and its inheritance was based on the SCA analysis. The Mawar and Chung varieties were good and can be used as the parent for tomato crosses. Furthermore, K/M, M/C and BC/K were the best single F1 crosses to be passed on to the F2 generation. The F1 K/M and K/C crosses were the best male and female parents to use for double-crosses. The recommended double-crosses include K/C//BC/M, and

BC/C//K/M, while for the F1 unbalanced three-way cross is K/C//K/M.

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