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COMBINING ABILITY AND HETEROTIC STUDIES ON HYBRID MELON (*Cucumis melo* L.) POPULATIONS FOR FRUIT YIELD AND QUALITY TRAITS

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SUMMARY

In different crop plants, combining ability and heterosis are used as important diagnostic tools for assessing the performance of parental genotypes and their hybrids. This research aimed to evaluate heterotic and combining ability effects in the diallel crosses of melon (*Cucumis melo* L.) for yield- and quality-related traits. Seven melon (*C. melo* L.) genotypes were grown and crossed in a complete diallel fashion to produce F_1 hybrids. During the 2019 crop season, 49 melon genotypes (7 parents + 42 F_1 hybrids) were grown in a randomized complete block design with three replications. Observations were made for seven characters. Analysis of variance revealed significant ($P \leq 0.01$) differences among the melon genotypes for harvest age, fruit flesh thickness, fruit total soluble solids, fruit length, and fruit diameter and merely significant differences ($P \leq 0.05$) for fruit weight. Combining ability analysis revealed that mean squares due to general combining ability (GCA) were significant for fruit diameter but were nonsignificant for all other traits. However, mean squares due to specific combining ability (SCA) were significant for all traits. The parental genotypes PK-165, PK-464, and PK-669 exhibited the highest and desirable GCA effects for yield and quality traits. Hence, these genotypes could be used to generate high-yielding hybrid/open-pollinated cultivars. GCA:SCA ratios further revealed that the traits of harvest age, fruit flesh thickness, fruit total soluble solids, fruit length, and fruit weight were controlled by dominant gene action, whereas fruit diameter was managed by additive and dominant genes. The majority of the traits were controlled by nonadditive gene action, verifying that the said breeding material could be efficiently used for the production of hybrid cultivars on the basis of heterotic effects.

Keywords: Diallel crosses, combining ability, heritability, heterosis, *Cucumis melo* L., choice of parents

Key findings: Six hybrids were identified as potential melon populations. The majority of the traits were also controlled by nonadditive gene action, showing room for the production of melon (*C. melo* L.) hybrid cultivars.

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INTRODUCTION

Melon (*Cucumis melo* L.) is an important summer-maturing fruit crop that is widely cultivated worldwide and has a vast range of different types (Paris *et al.*, 2012; Makful *et al.*, 2017). It has a high economic value and can be planted in tropical and subtropical regions (Ariesta and Rifah, 2016). Indonesia is one of the largest melon-producing countries in Southeast Asia, producing 117,344 tons (6859 ha) during 2016, 92,446 tons (15724 ha) during 2017, and 118,708 tons (6773 ha) during 2018 (FAO, 2018). However, in Indonesia, local melon production meets only approximately 40% of domestic needs, and the remaining 60% is imported (Annisa and Gustia, 2017).

The scarcity of improved melon cultivar seeds, which are still imported from Taiwan, Thailand, and Japan, is one of major hurdles encountered in increasing melon production in Indonesia (Zulfikri *et al.*, 2015). During 2017, the need for melon seed in Indonesia reached 4.1 tons, whereas domestic melon seed production was only 3.0 tons (BPS, 2017). Given the shortage of superior melon seeds, melon cultivation has become expensive and unprofitable for farming communities in Indonesia. Assembling hybrid melon cultivars with superior characters is an approach toward meeting the need for melon seeds in Indonesia and to reducing dependency on imported melon seeds.

Melon plant breeding programs aim to increase fruit yield, improve fruit quality, and enhanced resistance to major diseases (Khumaero *et al.*, 2014; Napolitano *et al*., 2020). High-yielding melon cultivars must have high production, uniform shape and size, and good fruit quality (Zalapa *et al.,* 2006). Character uniformity can be obtained from uniform melon genotypes that may be homozygous or heterozygous. Homozygotes are found in pure strains, whereas heterozygotes are found in hybrid cultivars. Hybrid melon cultivars are more desirable than pure melon strains because of their better characters and appearance and higher production (Choudary *et al.,* 2018).

Hybrid melon cultivars with desirable traits can be generated through diallel crosses performed among several parental genotypes to obtain the best new combinations (Barros *et al.*, 2011; Zhang and Kang, 1997). Diallel analysis can provide information on general combining ability (GCA) and specific combining ability (SCA) for parental genotypes and their hybrids, respectively (Chukwu *et al.*, 2016; Fasahat *et al.*, 2016). Such information is needed to identify potential parents with good combining ability and crosses with desired characters among Egyptian melon genotypes (Selim, 2019). The F_1 hybrids obtained through diallel crosses can have desirable heterotic effects and can exceed the parental genotypes in terms of performance (Amzeri, 2015; Liu *et al.*, 2019). Past research on combining ability and heterosis in complete diallel crosses reported desirable fruit weight and maturity in melon (Feyzan *et al.*, 2009). However, research on combining ability and heterosis using the complete diallel crosses of melon for yield and quality-related traits remains insufficient. Therefore, the present research was designed to evaluate the combining ability and heterotic effects in 7 × 7 diallel crosses of melon for yield and quality traits.

MATERIALS AND METHODS

Plant material and procedure

Seven melon genotypes, i.e., PK-165, PK-269, D-12, PK-464, PK-610, PK-669, and PK-361 (six lines originated from Sumenep Regency, Madura Island, Indonesia, and one line was introduced from China), were grown during June–September 2018 and were crossed in a complete diallel fashion to produce F_1 hybrids (Table 1, Figure 1). During the 2019 cropping season, 49 melon genotypes (7 parents + 42 F_1 hybrids) were grown in a randomized complete block design with three replications. The research location, i.e., Pamekasan, Madura Regency, Indonesia, is located at latitude 7°02 S and longitude 113°32 E at an altitude of 250 m. This location has the following conditions: average annual rainfall of 1461 mm, temperature of 27 °C–30 °C, alfisol soil type, and pH of 7.1.

The seeds of all the genotypes were grown in polybags with dimensions of 5 cm × 5 cm, and each experimental unit consisted of 10 plants. Ten-day-old melon plants were moved to beds with dimensions of 3.0 m × 1.2 m × 0.7 m (length × width × height) with plant and row spacings of 60 cm. Basic fertilization was carried out during tillage at the rate of 150 kg NPK ha^{-1} (2:2:1), and organic manure was applied at the rate of 10 ton ha^{-1}. NPK fertilizer was also applied at weekly intervals at the rate of 2 g per plant. After the plants had entered the generative phase, NPK fertilization was performed at the rate of 3 g per plant with weekly intervals. Insect pests of melon plants were controlled by using the insecticides Curacorn 500 EC and Decis 25 EC. Melon plant diseases were controlled by using the fungicides Antracol 70 WP, Dithane M-45 80 WP, and Agri-mycin 17.

Data collection and statistical analysis

For each parameter, the data were recorded by using five randomly selected melon plants in each subplot. The parameter measurements are presented in Table 2. All the recorded data were subjected to analysis of variance to test the null hypothesis that no differences existed among the melon parental genotypes and their F_1 populations (Steel *et al*., 1997). Duncan's new multiple range test (DMRT) was used for means separation and comparison after significance. The data of all the parameters of the seven melon parental genotypes and 42 F_1 hybrids were further subjected to combining ability analysis in accordance with Griffing's (1956) Method-I based on Eisenhart's Model-II (Singh and Chaudhary, 1985). Variance, combining ability, and heterosis out by using the PBTools, STAR, and Excel programs.

RESULTS AND DISCUSSION

Analysis of variance revealed significant ($P \leq 0.01$) differences among the melon (*C. melo* L.) analyses were carried genotypes for harvest age, fruit flesh thickness, fruit total soluble solids, fruit length, and fruit diameter and merely significant ($P \leq 0.05$) differences for fruit weight. These results indicated great genetic variability among the parental genotypes and their F_1 hybrids (Table 3).

Table 1. Descriptions of the melon parental genotypes used in the present research.

Parental genotypes	Fruit description
PK-165	Local line: large round fruit; green fruit skin; white flesh color; medium flesh; medium aroma; tight but uneven net
PK-269	Local line: large round fruit; yellow-green rind; white green flesh color; medium flesh; medium aroma; tight and even net
D-612	Introduction line: round and medium-sized fruit; green skin color; orange fruit flesh color; crispy flesh; no aroma; tenuous and uneven net
PK-464	Local line: large round fruit; green fruit skin; green-white flesh color; medium flesh; medium aroma; tight and even net
PK-610	Local line: large round fruit; green fruit skin; white flesh color; medium flesh; medium aroma; tight and even net
PK-669	Local line: large round fruit; cream-colored fruit skin; white green flesh color; soft flesh; fragrant aroma; tenuous and even net
PK-361	Local line: large round fruit; cream-colored fruit skin; white green flesh color; soft flesh; fragrant aroma; tight and even net

Figure 1. Melon parental genotypes used in the present study.

Table 2. Measurement of observation parameters.

Parameters	Measurement
Harvest age (days)	Calculated on the basis of the physiological maturity of melon fruits with the following characteristics, i.e., the net is visible, the skin color changes from green to yellow, the skin is fully colored, the fruit stalks turn yellow and the ring around the melon fruit stalk appears cracked (in melon mesh), and fragrant aroma
Fruit total soluble solids (°brix)	measured at the tip, middle, and base of melon fruit flesh by using a hand refractometer
Fruit flesh thickness (cm)	measured by cutting the melon fruit transversely at the end, middle, and bottom
Fruit length (cm)	measured from the base to the tip of the melon fruit
Fruit diameter (cm^2)	measured in the middle of the melon fruit
Fruit weight (g)	all the fruits were collected from each melon plant and then collectively weighed

Table 3. Analysis of variance for various yield-related traits in melon.

Sources of variation	d.f.	Mean squares					
		Harvest age	Fruit flesh thickness	Fruit total soluble solids	Fruit length	Fruit diameter	Fruit weight
Replications	2	0.13	0.01	1.31	0.29	0.32	80758.99
Genotypes	48	2.20**	0.83**	4.51**	2.99**	3.01**	61094.27*
Error	96	0.06	0.18**	0.38	0.27	0.26	40143.80
CV (%)	-	5.42	13.01	15.04	13.87	12.99	19.19

Note: *,** = significant at 5% and 1% level of probability; d.f. = degrees of freedom

GCA and SCA

Combined analysis of variance revealed that in *C. melo* L., mean squares due to GCA were significant for fruit diameter but were nonsignifcant for all other traits (Table 4). However, mean squares due to SCA were significant for all the traits. Akrami and Arzani (2019) revealed that in melon genotypes, mean squares due to GCA and SCA are significant for fruit diameter and other yield- and quality-related traits. The results further revealed that harvest age, fruit flesh thickness, fruit total soluble solids, fruit length, and fruit weight were controlled by dominant genes, whereas fruit diameter was controlled by additive and dominant gene action. Characters with high and significant GCA effects are controlled by additive genes, whereas traits with higher SCA effects than GCA effects are controlled by dominant genes (Ferreira *et al.*, 2004). The results showed a GCA:SCA ratio < 0.50 for all characters. Therefore, the action of dominant genes controlled all characters, and the melon cultivar assembly program should be directed toward the utilization of heterosis effects. Other studies on combining ability showed that the majority of the characters in cucumber (Bhutia *et al.*,

Table 4. Analysis of variance for combining ability, GCA:SCA variances and ratio, and heritability estimates for various traits in melon.

Sources of variation	d.f.	Mean squares					
		Harvest age	Fruit flesh thickness	Fruit total soluble solids	Fruit length	Fruit diameter	Fruit weight
GCA	6	0.46	0.13	2.25	1.51	1.65*	23639.92
SCA	21	0.68**	0.42**	1.93**	0.68**	0.65**	28417.69*
Reciprocals	21	0.87**	0.18**	0.86**	1.17**	1.17**	12152.30
Error	96	0.02	0.01	0.13	0.08	0.09	13415.43
σ^2g		0.00	0.00	0.03	0.06	0.07	1923.80
σ^2s		0.37	0.24	1.03	0.34	0.32	7260.30
σ^2r		0.42	0.09	0.37	0.55	0.54	7414.43
GCA:SCA ratio		0.00	0.00	0.05	0.06	0.30	0.35
σ^2A		0.00	0.00	0.11	0.24	0.29	0.00
σ^2D		1.49	0.94	4.11	1.36	1.29	34191.21
σ^2G		1.49	0.94	4.21	1.60	1,58	34191.21
σ^2E		0.02	0.01	0.13	0.07	0,08	13296.58
σ^2P		1.51	0.95	4.34	1.67	1,66	47487.79
h^2_{bs}		0.99	0.99	0.97	0.96	0.95	0.72
h^2_{ns}		0.00	0.00	0.02	0.14	0.17	0.00
h^2_{ns} / h^2_{bs}		0.00	0.00	0.02	0.15	0,18	0.00

Note : *,** = significant at 5% and 1% level of probability, respectively; df = degrees of freedom; GCA = general combining ability; SCA = specific combining ability; σ^2g = variance due to GCA; σ^2s = variance due to SCA; σ^2r = variance due to reciprocal; σ^2A = additive variance; σ^2D = dominant variance; σ^2G = genetic variance; σ^2E = environmental variance; σ^2P = phenotypic variance; h^2_{bs} = heritability in the broad sense; h^2_{ns} = heritability in the narrow sense

2017), sweet potato (Rukundo *et al*., 2017), and turnip rape (Sincik *et al*., 2014), are controlled by dominant genes.

For reciprocals, the mean squares were significant ($P \leq 0.01$) for harvest age, fruit flesh thickness, fruit total soluble solids, fruit length, and fruit diameter and nonsignificant for fruit weight (Table 4). Alhamdany (2013) revealed that mean squares due to reciprocal effects are significant for fruit diameter and fruit length in the full diallel crosses of melon. In *C. melo* L., the significance of reciprocal effects might be due to extrachromosomal influence on these characters.

Broad-sense heritability was high for all the characters and ranged from 0.72 to 0.99, which indicated the highest heritability (Stanfield, 1991) (Table 4). Narrow-sense heritability values for all the traits ranged from 0.00 to 0.17 and were lower than broad-sense heritability estimates. Past studies also revealed high broad-sense heritability values for various traits of *C. melo* L., i.e., fruit flesh thickness, fruit length, fruit diameter, and fruit weight (Ibrahim, 2012; Huda *et al.*, 2017; Sakulphrom *et al.*, 2018). Low narrow-sense heritability has been reported for fruit flesh thickness and fruit weight (Mohammadi *et al.*, 2014) and fruit total soluble solids (Javanmard *et al*., 2018) in melon genotypes. High broad-sense heritability values also indicated that most of the characters in melon were controlled by dominant gene action. The contribution of various additive genes could be inferred from the ratio of h^2_{ns}/h^2_{bs}, which was very low (0.00 to 0.18), indicating that that these characters were controlled by dominant genes (Table 4).

The GCA values for various characters of melon parental genotypes are presented in Table 5. Parents with positive GCA effects can be crossed well given their good combining ability for certain characters (Sprague and Tatum, 1942). Negative GCA values are also required and desirable for certain characters, such as earliness and harvest age (Susanto, 2018). The parents with negative GCA values for harvest age, namely, PK-269 (−0.32) and D-612 (−0.60), could be used to generate early-maturing melon cultivars. In melon parents, the GCA values for other traits varied from each other. PK-669 was the parent with high GCA for fruit total soluble solids. Furthermore, the parental cultivars PK-165, PK-464, and PK-669 exhibited the highest GCA effects for fruit weight. These cultivars can be used to assemble high-yielding hybrid melon cultivars with desirable quality. Parental genotypes with the most desirable and highest GCA have been recorded for okra (Wammanda *et al.*, 2010) and chili (Sitaresmi *et al.*, 2010). Such parental genotypes and their F_1 hybrids can be used to develop hybrid cultivars or open-pollinated cultivars through intensive selection in *C. melo* L.

In maize crossing programs aiming to produce profitable offspring, the parental cultivars that have high compatibility and combining ability with each other show the highest GCA values (Aguiar *et al.*, 2003; Iriany *et al.*, 2011). The results revealed that in general, the parental genotypes with low GCA effects produced cross combinations with the best and desirable SCA values. This situation indicated that in melon, low × low GCA parents performed well in producing promising hybrid populations with the best performance for growth, fruit yield, and quality-related traits. Parental genotypes with negative GCA values produced promising hybrids, viz., PK-361 × PK-165, and PK-5610 × D-612, with the best performance for fruit total soluble solids and fruit weight. Two other parents with negative GCA values also produced desirable F_1 hybrids, namely, PK-610 × D-612 and D-612 × PK-361, with desirable SCA effects and the highest fruit weight and other yield- and quality-related traits. A similar phenomenon in sweet corn is thought to be caused by the effects of beneficial genes in the two parental genotypes that hide nonuseful gene effects and the capability of the parents to combine with each other (Iriany *et al.*, 2011). The same findings were also reported by Akrami and Arzani for fruit total soluble solids (2019) and by Varinder and Vashisht for fruit weight (2018) in their diallel studies on *C. melo* L. The results further emphasized that the parental genotypes with negative GCA values produced the F_1 hybrid PK-361 × PK-669 with desirable SCA effects and harvest age. In diallel studies on melon, Feyzan *et al*. (2009) found that parental genotypes with negative GCA values resulted in offspring with desirable negative SCA effects for harvest age.

Table 5. Estimates for general and specific combining ability effects in parental genotypes and F1 hybrids for various traits in melon.

Parental genotypes & F1 hybrids	Harvest age	Fruit flesh thickness	Fruit total soluble solids	Fruit length	Fruit diameter	Fruit weight
Parental genotypes	General combining ability effects					
PK-165	0.09	0.25**	−0.02	−0.09	0.06	23.27*
PK-269	−0.32**	−0.13*	−0.02	−0.54**	−0.35**	3.27
D-612	−0.60**	−0.04	−0.20*	−0.28*	−0.61**	−60.94*
PK-464	0.28**	0.15	−0.08	−0.26*	0.29*	26.03*
PK-610	0.15*	−0.06	0.06	0.53**	0.21*	−45.22*
PK-669	0.18*	−0.28**	0.19*	0.46**	0.19	56.01**
PK-361	0.21*	0.11	−0.03	0.17	0.21*	−2.42
F1 hybrids	Specific combining ability effects					
PK-165 × PK-262	0.27*	0.06	−0.36*	−0.15	0.22*	44.73*
PK-165 × D-612	−0.76**	0.47**	−0.20*	−1.08**	−0.77**	99.11**
PK-165 × PK-464	0.22*	−0.23*	−0.22*	0.07	0.24*	21.81
PK-165 × PK-610	−0.70**	−0.01	0.26*	−0.72**	−0.68**	103.56**
PK-165 × PK-669	−0.64**	0.87**	0.50**	−0.15	−0.57**	−17.18
PK-165 × PK-361	0.45**	−0.84**	−0.15	0.80**	0.41*	25.92
PK-269 × PK-165	−0.03	0.00	0.33*	−0.83**	0.00	7.00
PK-269 × D-612	0.16*	0.01	0.53**	−0.46**	0.22*	116.94**
PK-269 × PK-464	0.15*	0.16*	0.48**	0.35*	0.15	0.13
PK-269 × PK-610	−0.51**	−0.46**	0.66**	0.23*	−0.52**	81.22**
PK-269 × PK-669	−0.20*	−0.41**	−0.59**	1.30**	−0.16	−35.01
PK-269 × PK-361	0.15*	0.20*	0.07	1.26**	0.14	58.92*
D-612 × PK-165	0.32**	−0.50**	−0.02	0.50**	0.25*	−12.83
D-612 × PK-269	0.40**	−0.04	−0.28*	1.00**	0.33*	−4.00
D-612 × PK-464	0.03	0.06	−0.16	0.42	−0.01	97.68**
D-612 × PK-610	0.57**	−0.73**	−0.25*	0.80**	0.58**	−235.36**
D-612 × PK-669	0.89**	0.66**	0.32*	1.71**	0.85**	12.20
D-612 × PK-361	−0.57**	0.28*	0.33*	−0.34*	−0.51**	108.30**
PK-464 × PK-165	0.32**	0.00	0.22*	−0.33*	0.33*	8.17
PK-464 × PK-269	1.73**	0.00	−0.25*	−0.50**	1.83**	−25.17
PK-464 × D-612	0.53**	0.00	0.00	−1.17**	0.42*	−6.83
PK-464 × PK-610	0.15*	−0.42**	0.17	−0.55**	0.17	67.13*
PK-464 × PK-669	−0.27**	−0.70**	0.16	0.18	−0.31*	−17.44
PK-464 × PK-361	0.11*	0.25*	−0.47**	0.64**	0.09	41.16*
PK-610 × PK-165	−0.50**	0.00	−0.37*	−0.33*	−0.50**	−28.67
PK-610 × PK-269	−0.25*	0.83**	−0.03	−0.17	−0.25*	−6.67
PK-610 × PK-612	0.38**	1.00**	−0.05	1.67**	0.42*	343.80**
PK-610 × PK-464	−1.40**	0.50**	0.06	0.00	−1.42**	−30.33
PK-610 × PK-669	1.08**	0.01	0.40*	−0.94**	1.03**	61.15*
PK-610 × PK-361	0.53**	1.30**	0.22*	−0.48**	0.59**	56.25*
PK-669 × PK-165	0.65**	−1.33**	0.00	−0.50**	0.58**	−11.17
PK-669 × PK-269	−1.25**	1.00**	0.12	−0.83**	−1.25**	−16.33
PK-669 × D-612	0.07	0.83**	0.25*	0.83**	0.17	36.00
PK-669 × PK-464	0.08	0.00	−0.40*	0.33*	0.08	−4.33
PK-669 × PK-610	−0.07	−0.50**	−0.02	0.00	0.00	−49.00*
PK-669 × PK-361	−0.70**	−0.15	−0.23*	−0.91**	−0.73**	−36.98
PK-361 × PK-165	−0.53**	0.33*	0.87**	−0.17	−0.58**	24.50
PK-361 × PK-269	−0.60**	0.00	−0.15	−0.17	−0.58**	−13.17
PK-361 × D-612	−0.20*	0.17	0.03	0.50**	−0.17	0.33
PK-361 × PK-464	−0.72**	0.00	0.25*	0.50**	−0.67**	16.50
PK-361 × PK-610	−0.55**	0.17	0.08	0.17	−0.58**	12.00
PK-361 × PK-669	−1.65**	−0.50**	−0.25*	0.33*	−1.58**	36.66

Note : *,** = significant at 5% and 1% level of probability, respectively; d.f. = degrees of freedom

Heterotic studies

Heterosis provides information on the best/worst performance for the quantitative traits of F_1 hybrids as compared with that of the mid (heterosis) and best parents (heterobeltiosis). In musk melon, the heterotic effects over mid and better parents are influenced by over-dominant genes in the parental genotypes; genes for quantitative characters are inherited by their descendants (Nerson, 2012). The percentage of heterosis and heterobeltiosis in F_1 populations with the best performance exceeds the average of both parents and the best parent (Fehr, 1987). Heterosis over the mid and high parent is mainly shown by parental genotypes with distant genetic backgrounds and kinship. In melon fruits, negative heterotic values for harvest age are sought after and found desirable because they reflect a melon genotype's superiority. Negative heterotic values for harvest age over mid and better parents were shown by three crosses, i.e., PK-269 × D-612, PK-610 × D-612, and PK-669 × PK-269, and ranged from −2.61% to −3.45%. Moreover, these genotypes were identified as the most early-maturing cultivars among all the cross combinations (Table 6).

Positive values of heterosis and heterobeltiosis for fruit flesh thickness, fruit total soluble solids, fruit length, fruit diameter, and fruit weight in *C. melo* L. are desirable. The highest positive heterotic values for fruit flesh thickness over mid and better parents were recorded in the crosses PK-269 × PK-5610, D-612 × PK-269, and PK-269 × PK-269 with the average mean values of 5.00, 5.03, and 5.07 cm, respectively. Among these three F_1 hybrids, PK-610 × PK-269 exhibited the highest heterosis and heterobeltiosis of 56.00% and 44.86%, respectively. The highest positive values of heterosis for fruit total soluble solids over the mid and better parents were observed in the F_1 hybrids D-612 × PK-669, PK-464 × D-612, and PK-464 × PK-361 with average mean values of 15.00, 13.33 and 13.00 °brix, respectively, and the highest percentages were shown by the cross D-612 × PK-669 (32.35% and 25.00%).

For fruit length characters, the highest heterosis and heterobeltiosis were recorded for the F_1 hybrids PK-269 × PK-464, PK-5610 × PK-464, and PK-361 × PK-5610 with maximum heterotic effects in the cross PK-5610 × PK-464 (14.00% and 10.68%, respectively) and average mean values of 18.83, 19.00, and 18.50 cm, respectively (Table 7). For fruit diameter, the highest values of heterosis over mid and better parents were found for the F_1 hybrids PK-269 × PK-464, PK-5610 × PK-464, and PK-361 × PK-5610 with mean values of 18.43, 18.45, and 18.12 cm^2, respectively. The highest heterotic and heterobeltiotic values for fruit diameter were found for the cross PK-5610 × PK-464 (0.12% and 0.08%, respectively). Furthermore, promising heterosis and heterobeltiosis for fruit weight were exhibited by the F_1 hybrids PK-464 × PK-669, PK-610 × PK-464, and PK-669 × PK-610 with the average mean values of 2239.67, 2309.33, and 2300.33 g, respectively. The highest heterosis for fruit weight over mid and better parents were noted in F_1 hybrid PK-669 × PK-5610 (19.38% and 15.42%, respectively).

Table 6. Estimates of heterosis over the mid parent (MP) and better parent (HP) for harvest age, fruit flesh thickness, and total soluble solids in melon.

F1 hybrids	Harvest age			Fruit flesh thickness			Fruit total soluble solids		
	Means (days)	MP (%)	HP (%)	Means (cm)	MP (%)	HP (%)	Means (°brix)	MP (%)	HP (%)
PK-165 × PK-262	58.00 $^{\text{c}}$	0.00	0.00	4.27 $^{\text{e–i}}$	7.20	−4.40	10.67 $^{\text{abc}}$	−3.00	−19.98
PK-165 × D-612	58.00 $^{\text{c}}$	0.87	1.72	4.00 $^{\text{de}}$	−0.41	−10.45	11.33 $^{\text{a–e}}$	−5.58	−15.03
PK-165 × PK-464	58.00 $^{\text{c}}$	−0.85	−1.69	4.23 $^{\text{d–h}}$	−2.38	−5.30	11.67 $^{\text{a–f}}$	−2.75	−12.48
PK-165 × PK-610	58.00 $^{\text{c}}$	0.00	0.00	4.27 $^{\text{e–i}}$	14.38	−4.40	11.67 $^{\text{a–f}}$	−17.62	−22.20
PK-165 × PK-669	57.33 $^{\text{c}}$	−0.30	0.57	5.00 $^{\text{jk}}$	15.83	11.94	12.00 $^{\text{b–f}}$	−5.26	−10.00
PK-165 × PK-361	57.67 $^{\text{bc}}$	0.30	1.16	5.00 $^{\text{jk}}$	11.52	11.94	13.00 $^{\text{efg}}$	4.00	−2.50
PK-269 × PK-165	58.00 $^{\text{c}}$	0.00	0.00	3.60 $^{\text{abc}}$	−9.62	−19.40	12.33 $^{\text{c–f}}$	12.09	−7.53
PK-269 × D-612	56.00 $^{\text{a}}$	−2.61	−1.72	4.47 $^{\text{f–i}}$	26.51	25.33	12.00 $^{\text{b–f}}$	24.14	12.50
PK-269 × PK-464	58.00 $^{\text{c}}$	−0.85	−1.69	4.47 $^{\text{f–i}}$	16.10	6.43	11.33 $^{\text{a–e}}$	17.21	6.22
PK-269 × PK-610	58.00 $^{\text{c}}$	0.00	0.00	5.00 $^{\text{jk}}$	53.85	42.86	12.33 $^{\text{c–f}}$	4.20	−17.80
PK-269 × PK-669	58.00 $^{\text{c}}$	0.87	1.72	4.03 $^{\text{def}}$	5.13	−3.28	12.67 $^{\text{d–g}}$	22.61	5.58
PK-269 × PK-361	58.00 $^{\text{c}}$	0.87	1.72	4.20 $^{\text{d–h}}$	5.00	−6.67	13.00 $^{\text{efg}}$	27.87	11.43
D-612 × PK-165	59.00 $^{\text{de}}$	2.61	1.72	4.03 $^{\text{def}}$	0.33	−9.78	10.33 $^{\text{ab}}$	−13.92	−22.53
D-612 × PK-269	59.33 $^{\text{ef}}$	3.18	2.29	5.03 $^{\text{k}}$	42.36	41.03	10.00 $^{\text{a}}$	3.45	−6.25
D-612 × PK-464	58.00 $^{\text{c}}$	0.00	−1.69	4.00 $^{\text{de}}$	3.00	−4.76	11.00 $^{\text{a–d}}$	3.13	3.13
D-612 × PK-610	58.00 $^{\text{c}}$	0.87	0.00	4.03 $^{\text{def}}$	22.74	12.99	15.00 $^{\text{h}}$	16.88	0.00
D-612 × PK-669	59.00 $^{\text{de}}$	3.51	3.51	5.00 $^{\text{jk}}$	29.31	20.00	15.00 $^{\text{h}}$	32.35	25.00
D-612 × PK-361	58.33 $^{\text{cde}}$	2.33	2.33	4.57 $^{\text{hij}}$	13.31	1.56	12.33 $^{\text{c–f}}$	10.42	5.69
PK-464 × PK-165	58.00 $^{\text{c}}$	−0.85	0.00	3.80 $^{\text{bcd}}$	−12.31	−14.93	12.33 $^{\text{c–f}}$	2.75	−7.53
PK-464 × PK-269	58.00 $^{\text{c}}$	−0.85	0.00	4.97 $^{\text{jk}}$	29.09	18.33	12.33 $^{\text{c–f}}$	27.55	15.59
PK-464 × D-612	58.00$^{\text{c}}$	0.00	1.69	4.00 $^{\text{de}}$	3.00	−4.76	13.33 $^{\text{fgh}}$	24.97	24.97
PK-464 × PK-610	58.00 $^{\text{c}}$	−0.85	0.00	3.97 $^{\text{cde}}$	10.28	−5.48	12.00 $^{\text{b–f}}$	−6.49	−20.00
PK-464 × PK-669	57.00 $^{\text{b}}$	−1.72	0.00	4.20 $^{\text{d–h}}$	0.40	0.00	13.00 $^{\text{efg}}$	14.71	8.33
PK-464 × PK-361	58.33 $^{\text{cde}}$	0.57	2.25	4.00 $^{\text{de}}$	6.67	−11.11	13.33 $^{\text{fgh}}$	19.37	14.26
PK-610 × PK-165	58.00 $^{\text{c}}$	0.00	0.00	5.00 $^{\text{jk}}$	33.93	11.94	12.33 $^{\text{c–f}}$	−12.96	−17.80
PK-610 × PK-269	56.33 $^{\text{a}}$	−2.88	−2.88	5.07 $^{\text{k}}$	56.00	44.86	12.67 $^{\text{d–g}}$	7.07	−15.53
PK-610 × PK-612	56.00 $^{\text{a}}$	−2.61	−1.72	4.10 $^{\text{d–g}}$	24.87	14.95	11.67 $^{\text{a–f}}$	−9.06	−22.20
PK-610 × PK-464	57.00 $^{\text{b}}$	−2.56	−3.39	5.00 $^{\text{jk}}$	38.89	19.05	12.00 $^{\text{b–f}}$	−6.49	−20.00
PK-610 × PK-669	57.00 $^{\text{b}}$	−0.87	0.00	4.97 $^{\text{jk}}$	38.70	19.28	12.33 $^{\text{c–f}}$	−8.67	−17.80
PK-610 × PK-361	59.33 $^{\text{ef}}$	3.18	4.02	4.67 $^{\text{jk}}$	24.53	3.78	12.67 $^{\text{d–g}}$	−4.97	−15.53
PK-669 × PK-165	60.00 $^{\text{f}}$	4.35	3.45	5.00 $^{\text{jk}}$	15.83	11.94	13.00 $^{\text{efg}}$	−3.70	−13.33
PK-669 × PK-269	56.00 $^{\text{a}}$	−2.61	−3.45	3.80 $^{\text{bcd}}$	−0.87	−8.80	14.33 $^{\text{gh}}$	6.15	−4.47
PK-669 × D-612	57.33 $^{\text{bc}}$	0.58	0.58	4.50 $^{\text{ghi}}$	16.38	8.00	13.33 $^{\text{fgh}}$	−1.26	−11.13
PK-669 × PK-464	57.00 $^{\text{b}}$	−1.72	−3.39	5.00 $^{\text{jk}}$	19.52	19.05	12.33 $^{\text{c–f}}$	−8.67	−17.80
PK-669 × PK-610	58.00 $^{\text{c}}$	0.87	0.00	5.00 $^{\text{jk}}$	39.53	20.00	12.33 $^{\text{c–f}}$	−8.67	−17.80
PK-669 × PK-361	57.00 $^{\text{b}}$	0.00	0.00	4.00 $^{\text{de}}$	−7.69	−11.11	12.33 $^{\text{c–f}}$	−8.67	−17.80
PK-361 × PK-165	57.00 $^{\text{b}}$	−0.87	−1.72	3.27 $^{\text{a}}$	−27.06	−27.33	13.33 $^{\text{fgh}}$	6.64	−0.03
PK-361 × PK-269	58.00 $^{\text{c}}$	0.87	0.00	4.50 $^{\text{ghi}}$	12.50	0.00	13.33 $^{\text{fgh}}$	31.11	14.26
PK-361 × D-612	58.00 $^{\text{c}}$	1.75	1.75	4.50 $^{\text{ghi}}$	11.57	26.17	11.33 $^{\text{a–f}}$	1.46	−2.89
PK-361 × PK-464	58.33 $^{\text{cde}}$	0.57	−1.14	3.50 $^{\text{ab}}$	−19.54	−22.22	12.33 $^{\text{c–f}}$	10.42	5.69
PK-361 × PK-610	59.00 $^{\text{de}}$	2.61	1.72	4.50 $^{\text{ab}}$	20.00	0.00	12.33 $^{\text{c–f}}$	−7.52	−17.80
PK-361 × PK-669	58.00 $^{\text{c}}$	1.75	1.75	4.50 $^{\text{ghi}}$	3.85	0.00	11.67 $^{\text{a–f}}$	−1.38	−2.75

Note: Numbers in one column followed by the same letter show no significant difference based on the DMRT test at the level of α = 5%

Table 7. Estimates of heterosis (%) over the mid parent (MP) and better parent (HP) for fruit length, fruit diameter, and fruit weight in melon.

F1 hybrids	Fruit length			Fruit diameter			Fruit weight		
	Means (cm)	MP (%)	HP (%)	Means (cm^2)	MP (%)	HP (%)	Means (g)	MP (%)	HP (%)
PK-165 × PK-262	16.83 $^{a-f}$	−1.96	−7.36	16.50 $^{a-c}$	−0.04	−0.11	1941.67 $^{a-f}$	0.98	−2.25
PK-165 × D-612	15.83 ^{abc}	−5.49	−12.86	15.45 $^{a-d}$	−0.08	−0.16	1868.00 $^{a-d}$	−2.14	−5.96
PK-165 × PK-464	17.83 $^{d-h}$	0.92	−1.85	17.44 ^{afg}	−0.02	−0.06	2170.00 $^{c-g}$	8.30	7.37
PK-165 × PK-610	16.00 ^{abc}	−6.80	−11.93	15.45 $^{a-d}$	−0.11	−0.16	1956.33 $^{a-f}$	1.71	−1.51
PK-165 × PK-669	17.17 $^{c-g}$	−2.81	−5.49	17.04 $^{c-g}$	−0.04	−0.08	2047.67 $^{a-g}$	2.92	2.74
PK-165 × PK-361	17.00 $^{a-g}$	−4.23	−6.42	16.47 $^{a-f}$	−0.07	−0.11	2025.33 $^{a-g}$	3.67	1.96
PK-269 × PK-165	16.83 $^{a-f}$	−1.96	−7.36	16.46 $^{a-f}$	−0.05	−0.11	1950.33 $^{a-f}$	1.43	−1.81
PK-269 × D-612	16.50 $^{a-d}$	4.76	2.06	16.25 $^{a-f}$	0.04	0.01	1819.33 ^{a}	−1.41	−2.15
PK-269 × PK-464	18.83 ^{gh}	12.98	9.69	18.43 ^{g}	0.11	0.08	2183.67 ^{afg}	12.55	8.05
PK-269 × PK-610	16.00 ^{abc}	−1.03	−1.03	15.46 $^{a-d}$	−0.04	−0.04	1935.67 $^{a-f}$	4.07	4.03
PK-269 × PK-669	15.33 ^{ab}	−8.02	−10.70	15.06 ^{ab}	−0.09	−0.12	1797.00 ^{a}	−6.71	−9.83
PK-269 × PK-361	16.33 $^{a-d}$	−2.51	−5.79	16.06 $^{a-e}$	−0.03	−0.06	1983.33 $^{a-f}$	4.93	3.24
D-612 × PK-165	15.33 ^{ab}	−8.48	−15.61	15.06	−0.10	−0.19	1854.00 ^{ab}	−2.87	−6.66
D-612 × PK-269	15.83 ^{abc}	0.51	−2.08	15.43 $^{a-d}$	−0.01	−0.04	1930.67 $^{a-f}$	4.62	3.84
D-612 × PK-464	17.00 $^{a-g}$	4.62	−0.97	17.04 $^{c-g}$	0.06	0.00	2064.33 $^{a-g}$	7.17	2.14
D-612 × PK-610	17.50 $^{c-h}$	11.11	8.25	17.23 $^{d-g}$	0.11	0.07	2080.67 $^{a-g}$	12.71	11.82
D-612 × PK-669	17.50 $^{c-h}$	7.69	1.94	17.24 $^{d-g}$	0.07	0.01	2222.67 $^{e-g}$	16.24	11.52
D-612 × PK-361	15.83 ^{abc}	−3.08	−8.67	15.43 $^{a-d}$	−0.04	−0.10	1922.67 $^{a-g}$	2.48	0.09
PK-464 × PK-165	17.17 $^{c-g}$	−2.81	−5.49	17.04 $^{c-g}$	−0.04	−0.08	2037.67 $^{a-g}$	1.70	0.82
PK-464 × PK-269	15.17 ^{a}	−8.98	−11.63	15.22 ^{abc}	−0.08	−0.11	1855.00 ^{abc}	−4.39	−8.21
PK-464 × D-612	16.17 $^{a-d}$	−0.49	−5.81	16.03 $^{a-e}$	0.00	−0.06	1929.33 $^{a-f}$	0.16	−4.54
PK-464 × PK-610	16.17 $^{a-d}$	−2.98	−5.81	16.03 $^{a-e}$	−0.03	−0.06	1961.67 $^{a-f}$	1.07	−2.94
PK-464 × PK-669	17.17 $^{c-g}$	0.02	0.02	17.04 $^{c-g}$	0.00	0.00	2239.67 ^{fg}	11.59	10.82
PK-464 × PK-361	16.83 $^{a-f}$	−2.43	−2.90	16.44 $^{a-f}$	−0.04	−0.04	2096.33 $^{a-g}$	6.36	3.73
PK-610 × PK-165	17.00 $^{a-g}$	−0.97	−6.42	16.45 $^{a-f}$	−0.05	−0.11	2186.67 ^{efg}	13.68	10.09
PK-610 × PK-269	16.50 $^{a-d}$	2.06	2.06	16.24 $^{a-f}$	0.01	0.01	2031.33 $^{a-g}$	9.21	9.17
PK-610 × PK-612	16.67 $^{a-e}$	5.84	3.11	16.26 $^{a-f}$	0.05	0.01	2028.67 $^{a-g}$	9.90	9.03
PK-610 × PK-464	19.00 ^{h}	14.00	10.68	18.45 ^{g}	0.12	0.08	2309.33 ^{g}	18.99	14.27
PK-610 × PK-669	18.33 $^{e-h}$	9.98	6.78	18.05 ^{fg}	0.09	0.06	2202.33 ^{efg}	14.30	10.50
PK-610 × PK-361	17.33 $^{c-h}$	3.46	−0.02	17.05 $^{c-g}$	0.03	0.00	2200.00 ^{efg}	16.35	14.52
PK-669 × PK-165	16.00 ^{abc}	−9.43	−11.93	15.45 $^{a-d}$	−0.13	−0.16	1955.67 $^{a-f}$	−1.71	−1.87
PK-669 × PK-269	17.83 $^{d-h}$	6.98	3.86	17.44 ^{efg}	0.05	0.02	2220.00 ^{efg}	15.25	11.39
PK-669 × D-612	17.17 $^{c-h}$	5.66	0.02	17.06 $^{c-g}$	0.06	0.00	2150.67 $^{b-g}$	12.47	7.91
PK-669 × PK-464	17.00 $^{a-g}$	−0.97	−0.97	16.46 $^{a-f}$	−0.03	−0.03	2089.33 $^{a-g}$	4.10	3.38
PK-669 × PK-610	18.33 $^{e-h}$	9.98	6.78	18.06 ^{fg}	0.09	0.06	2300.33 ^{g}	19.38	15.42
PK-669 × PK-361	15.00 ^{a}	−13.04	−13.46	14.45 ^{a}	−0.15	−0.15	1862.00 $^{a-d}$	−4.85	−6.57
PK-361 × PK-165	18.17 $^{e-h}$	2.37	0.02	18.04 ^{fg}	0.01	−0.02	2201.67 ^{efg}	12.69	10.84
PK-361 × PK-269	17.50 $^{c-h}$	4.48	0.96	17.25 $^{d-g}$	0.04	0.07	2166.33 $^{b-g}$	14.61	12.77
PK-361 × D-612	16.17 $^{a-d}$	−1.00	−6.71	16.04 $^{a-e}$	0.00	0.07	1963.33 $^{a-f}$	4.65	2.20
PK-361 × PK-464	18.17 $^{e-h}$	5.33	4.83	18.05 ^{fg}	0.06	0.06	2227.67 ^{efg}	13.02	10.23
PK-361 × PK-610	18.50 ^{fgh}	10.45	6.73	18.12 ^{fg}	0.10	0.11	2176.00 $^{d-g}$	15.08	13.27
PK-361 × PK-669	18.17 $^{e-h}$	5.33	4.83	18.05 ^{fg}	0.06	0.06	2159.33 $^{b-g}$	10.34	8.35

Note: Numbers in one column followed by the same letter show no significant difference based on the DMRT test at the level of $\alpha = 5\%$

Selection of potential parental genotypes and F1 hybrids

In the majority of crop plants, combining ability and heterotic effects are needed to determine potential parents and their hybrids for assembling hybrids and open-pollinated cultivars in future breeding programs (Wiguna, 2015). A hybrid with high SCA values does not always exhibit the best heterosis because for SCA, all the cross combinations are tested and compared, whereas for heterosis, the F_1 hybrid is compared only with the two parents. Therefore, for the selection of a promising hybrid, attention must be paid to the GCA of the parental genotypes, the SCA of F_1 hybrids, and the estimations of heterosis and heterobeltiosis in the said hybrid. The best hybrid can be produced and selected through the cross-breeding of parental genotypes on the basis of desirable GCA and SCA effects and heterosis over mid and better parents for the desired traits (Roy, 2000).

The results of this study revealed that melon hybrid cultivars with the best mean performance for desirable traits, i.e., early maturity and high sugar content, could be developed on the basis of GCA, SCA, and heterotic effects. In melon fruits, the highest production is based on fruit weight. In muskmelon, fruit flesh thickness, fruit length, and fruit diameter are supporting characters and are positively correlated with fruit weight (Mehta *et al*, 2009; Sakulphrom, 2018). In melon, fruit weight is high if it exceeds 2000 g, and harvest age is considered as early if it is less than 70 days (IPGRI, 2003). In melon, fruit total soluble solids is the most desirable trait and must be higher or equal to 10 °brix for

Table 8. Average of fruit weight (>2000 g), heterosis value (%) and combining ability.

F1 hybrids	MP (%)	HP (%)	Means (g)	SCA effects	GCA effects
PK-610 × PK-464	14.00	10.68	2309.33	−30.30	PK-165 = 23.27
PK-669 × PK-610	9.98	6.78	2300.33	−49.00	PK-464 = 26.03
PK-464 × PK-669	0.02	0.02	2239.67	−17.44	PK-361 = 56.01
PK-361 × PK-464	5.33	4.83	2227.67	16.50	
D-612 × PK-669	7.69	1.94	2222.67	12.20	
PK-669 × PK-269	6.98	3.86	2220.00	−16.33	
PK-610 × PK-669	9.98	6.78	2202.33	61.15	
PK-361 × PK-165	2.37	0.02	2201.67	24.50	
PK-610 × PK-361	3.46	−0.02	2200.00	56.25	
PK-610 × PK-165	−0.97	−6.42	2186.67	−28.67	
PK-269 × PK-464	12.98	9.69	2183.67	0.13	
PK-361 × PK-610	10.45	6.73	2176.00	12.00	
PK-165 × PK-464	0.92	−1.85	2170.00	44.73	
PK-361 × PK-269	4.48	0.96	2166.33	−13.17	
PK-361 × PK-669	5.33	4.83	2159.33	36.66	
PK-669 × D-612	5.66	0.02	2150.67	36.00	
PK-464 × PK-361	−2.43	−2.9	2096.33	41.16	
PK-669 × PK-464	−0.97	−0.97	2089.33	−4.33	
D-612 × PK-610	11.11	8.25	2080.67	−235.36	
D-612 × PK-464	4.62	−0.97	2064.33	97.68	
PK-165 × PK-669	−2.81	−5.49	2047.67	−17.18	
PK-464 × PK-165	−2.81	−5.49	2037.67	8.17	
PK-610 × PK-269	2.06	2.06	2031.33	−6.67	
PK-610 × D-612	5.84	3.11	2028.67	343.80	
PK-165 × PK-361	−4.23	−6.42	2025.33	25.92	

commercial varieties (United Nations Economic Commission for Europe, 2017).

For melons, the recommended harvest age is the early age category (56–60 days), and fruit total soluble solids should be equal or more than 10 °brix (10–15 °brix). All the present F_1 hybrids meet the criteria for superior melon cultivars, and the direction of breeding should be based on these two important traits. Fruit weight should be considered further because the other two characters, i.e., harvest age and fruit total soluble solids, meet the criteria of superiority in all the cross combinations. The highest production could be obtained from the diallel crosses of melon genotypes with the highest fruit weight (>2000 g). Several F_1 hybrids with fruit weights of above 2000 g with promising heterosis and combining ability were observed in the present melon diallel populations (Table 8).

The selection of cross combinations to be released as hybrid cultivars is mainly based on GCA and SCA values, heterosis, and heterobeltiosis. The best hybrid must have desirable GCA parents, attractive SCA values, and heterotic effects. On the basis of these criteria, six melon F_1 hybrids, namely, PK-361 × PK-464, D-612 × PK-669, PK-610 × PK-669, PK-361 × PK-165, PK-361 × PK-669, and PK-669 × D-612, were identified and selected as superior hybrid cultivars with good yield potential and desirable quality traits. These six hybrids had desirable mean values for harvest age (56–59 days), fruit total soluble solids (11.67–15.00 °brix), and fruit weight (2150.62–2227.67 g). Thus, these promising hybrids can be used as candidate genotypes for release as hybrid melon cultivars with early maturity, high sugar content, and increased yield with desirable quality.

CONCLUSIONS

Most traits, i.e., harvest age, fruit flesh thickness, fruit total soluble solids, fruit length, and fruit weight, were controlled by dominant genes. GCA:SCA ratios were less than 0.50 for all the traits, confirming that all the characters were controlled by dominant gene action. Therefore, the melon cultivar assembly program should be directed toward the utilization of heterotic effects. The parental genotypes PK-165, PK-464, and PK-669 exhibited high GCA values for fruit weight. The F_1 hybrids PK-361 × PK-464, D-612 × PK-669, PK-610 × PK-669, PK-361 × PK-165, PK-361 × PK-669, and PK-669 × D-612 were identified and selected as promising cross combinations on the basis of GCA and SCA values and heterotic effects for harvest age, fruit total soluble solids, and fruit weight. These candidate genotypes could be used as a source population for the development of melon hybrid cultivars with early maturity and increased sugar content, yield, and quality.

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