

Diallel analysis of hybrid combinations of watermelon grown in an agroecological production system

Análise dialélica de combinações híbridas de melancia cultivadas em sistema de produção agroecológica

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ABSTRACT – Watermelon is an important crop in the Northeast region of Brazil; therefore, the development of lines and cultivars adapted to the edaphoclimatic conditions of this region and to agroecological production systems is essential for farmers and the environment. This study estimated general combining ability (GCA) and specific combining ability (SCA), as well as their reciprocal effects, for earliness and for yield and fruit traits in watermelon genotypes. The experiments were conducted at the Universidade Federal do Vale do São Francisco (UNIVASF), in Petrolina, PE, Brazil, during two evaluation cycles. A randomized block design was used, with 19 treatments, three replications, and plots containing five plants. The data were subjected to analysis of variance and diallel analysis. Non-additive gene effects predominated for 58.8% of the variables. The GCA analysis showed that the parents BGH-UNIVASF 177 and BGH-UNIVASF 67 were the most promising for obtaining hybrids with higher marketable fruit yield and greater fruit weight. The parent 'Sugar Baby' was identified as a good combiner for earliness, fruit diameter, and soluble solids content. The parent BGH-UNIVASF 189 was identified as a good combiner for total fruit yield and soluble solids content. Hybrid 3×4 was the most promising for the greatest number of agronomically important traits. Hybrids 1×2, 1×4, and 2×4 were promising for earliness, soluble solids content, fruit yield, good vegetative development, and lower fruit weight. No reciprocal effects were found for the traits evaluated.

RESUMO – A melancia é uma cultura importante na região Nordeste do Brasil; portanto, o desenvolvimento de linhagens e cultivares adaptadas às condições edafoclimáticas dessa região e aos sistemas de produção agroecológica é essencial para os agricultores e o meio ambiente. Este estudo estimou a capacidade geral de combinação (CGC), a capacidade específica de combinação (CEC), bem como seus efeitos recíprocos para precocidade e caracteres de produção e de fruto, em genótipos de melancia. Os experimentos foram conduzidos na Universidade Federal do Vale do São Francisco, em Petrolina, PE, Brasil, durante dois anos de avaliação. Utilizou-se o delineamento em blocos casualizados, com 19 tratamentos, três repetições e parcelas contendo cinco plantas. Os dados foram submetidos à análise de variância e à análise dialélica. Os efeitos gênicos não aditivos predominaram em 58,8% das variáveis. A análise da CGC mostrou que os genitores BGH-UNIVASF 177 e BGH-UNIVASF 67 foram os mais promissores para a obtenção de híbridos com maior produtividade de frutos comercializáveis e maior massa de frutos. O genitor 'Sugar Baby' foi identificado como bom combinador para precocidade, diâmetro de fruto e teor de sólidos solúveis. O genitor BGH-UNIVASF 189 foi identificado como bom combinador para produtividade total de frutos e teor de sólidos solúveis. O híbrido 3×4 foi o mais promissor para o maior número de características de importância agrônoma. Os híbridos 1×2, 1×4 e 2×4 foram promissores para precocidade, teor de sólidos solúveis, produtividade de frutos, bom desenvolvimento vegetativo e menor massa de frutos. Não foram encontrados efeitos recíprocos para as características avaliadas.

Keywords: *Citrullus lanatus*. Plant breeding. Organic agriculture.

Palavras-chave: *Citrullus lanatus*. Melhoramento genético vegetal. Agricultura orgânica.

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INTRODUCTION

Watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] is a highly valued vegetable crop in several regions of the world, and the six largest producers are China, Turkey, India, Iran, Algeria, and Brazil, respectively (FAOSTAT, 2020). In Brazil, the Northeast region has become established over the years as the largest watermelon-producing region in the country, with an annual output of 731,087 Mg grown on 40,534 ha, representing approximately 37% of national production (IBGE, 2024). Among the states in the Northeast region, the three largest producers are Bahia (231,934 Mg), Pernambuco (152,425 Mg), and Rio Grande do Norte (142,614 Mg), which together account for approximately 72.1% of this production (IBGE, 2024).

In 2024, Brazil exported 132,550 Mg of fresh watermelon, generating revenue of USD 73.6 million. Among the exporting states, Rio Grande do Norte and Ceará accounted for the largest shares, with 62% and 21%, respectively (CONAB, 2025). Watermelon cultivation has substantial socioeconomic importance in the Northeast region of Brazil because it is grown by small-, medium-, and large-scale producers under different management systems and

requires intensive labor, which contributes to employment and income generation.

Despite its importance, watermelon production in Brazil is concentrated in few cultivars (LIMA, 2014); Crimson Sweet and its hybrids predominate throughout Brazil (TAVARES et al., 2018). In addition, several cultivars were introduced from other countries and therefore were developed under different environmental conditions, which imposes limitations, including additional costs for plant protection treatments used to control pests and diseases, an increased number of pesticide applications, and greater risks of intoxication in the field and consumer exposure to pesticide residues in fruits (LIMA, 2014). Thus, given the relevance of the crop and new market demands for increasingly practical and nutritious products free of pesticide residues (TAVARES et al., 2018), cultivars adapted to the region and to agroecological and organic production systems must be developed.

In this context, Spagnuolo et al. (2016) indicated the need to use agroecological principles to develop cultivars for organic or sustainability-based agriculture by using germplasm adapted to local conditions and recovering traditional populations. In addition, cultivars developed for conventional systems lack important traits required under sustainability-based production conditions (LE CAMPION et al., 2020).

Thus, to support research, several samples of watermelon accessions from traditional farming systems in the Semiarid region of Pernambuco were collected in mid-2015. These materials, which showed plant and fruit variability, formed, together with other vegetable species, the Vegetable Germplasm Bank at the Universidade Federal do Vale do São Francisco – UNIVASF (BGH-UNIVASF), which contained approximately 300 accessions at that time.

On this basis, Sousa (2017) evaluated 27 watermelon accessions from traditional farming systems in the Sertão

region of Pernambuco grown in an agroecological production system and found that three accessions (BGH-UNIVASF 67, 177, and 189) had superior agronomic performance compared with commercial cultivars, mainly for mean fruit weight and marketable yield; therefore, these accessions were inferred to be promising materials for the watermelon breeding program in an agroecological system.

These accessions, together with the cultivar 'Sugar Baby', were intercrossed, resulting in 12 hybrid combinations. Diallel analysis allows promising parents and hybrid combinations to be selected based on parameter estimates and allows the genetic effects controlling the evaluated traits to be understood (CRUZ; REGAZZI; CARNEIRO, 2012). In addition, Ferreira et al. (2002) emphasized the need to perform diallel crosses in both directions (hybrids and reciprocals) because responses may differ when a parent is used as a pollen donor or recipient.

In this context, this study estimated the general (GCA) and specific (SCA) combining ability and their reciprocal effects for earliness, yield, and fruit traits to support the watermelon breeding program for agroecological production systems.

MATERIAL AND METHODS

The experiment was conducted in the Olericulture and Agroecology Sector of the Universidade Federal do Vale do São Francisco (UNIVASF; Federal University of Vale do São Francisco), Agricultural Sciences Campus, Petrolina, PE, Brazil (9°19'10.47"S, 40°33'48.91"W; 400 m altitude), during two evaluation cycles. The first evaluation cycle was conducted from August to December 2017, and the second was conducted from June to September 2018. Climatic data were collected during the 2017 (Table 1) and 2018 (Table 2) evaluation cycles of the experiment.

Table 1. Maximum, mean, and minimum temperature (T), mean relative humidity (RH), rainfall (RF), evapotranspiration (ETo), and mean global radiation (GR) recorded during the first evaluation year of the experiment (2017).

Month	T (°C)			RH	RF	ETo	GR
	Maximum	Mean	Minimum	(%)	(mm)	(mm month ⁻¹)	(MJ m ⁻²)
Sep 17	30.3	24.9	19.4	56.50	0.0	138.8	20.6
Oct 17	33.8	27.4	21.0	47.83	0.0	181.2	25.8
Nov 17	34.5	28.7	22.8	46.96	4.6	164.9	24.9
Dec 17	34.3	28.8	23.2	48.80	10.2	163.4	23.6

Table 2. Maximum, mean, and minimum temperature (T), mean relative humidity (RH), rainfall (RF), evapotranspiration (ETo), and mean global radiation (GR) recorded during the second evaluation year of the experiment (2018).

Month	T (°C)			RH	RF	ETo	GR
	Maximum	Mean	Minimum	(%)	(mm)	(mm month ⁻¹)	(MJ m ⁻²)
Jun 18	30.7	25.0	19.3	57.73	20.6	12.6	18.3
Jul 18	30.3	24.5	18.7	54.20	25.8	133.5	19.7
Aug 18	31.7	25.5	19.2	50.64	24.9	149.3	21.7
Sep 18	33.4	26.9	20.5	47.88	23.6	165.2	24.9

The experiments were conducted using crop-specific management and plant protection practices based on agroecological principles, including the incorporation of green manure plants and organic compost into the soil, biofertilizer application, spray mixtures for pest and disease control, and green manure species to promote natural enemies (SOUZA; RESENDE, 2014).

A randomized block design was used, with 19

treatments, three replications, and plots containing five evaluated plants. The treatments consisted of four parents (BGH-UNIVASF 67, 177, 189, and the commercial cultivar 'Sugar Baby'), their 12 crosses, including hybrids and reciprocals, and three commercial cultivars (Crimson Sweet, Pérola, and Charleston Gray). The parents and their hybrids were designated and ordered as shown in Table 3.

Table 3. Designation and distribution of the parents and their hybrids in the experiment.

Male parent Female parent				
	BGH-UNIVASF 177- parent 1	BGH-UNIVASF 189 - parent 2	BGH-UNIVASF 67- parent 3	'Sugar Baby'- parent 4
BGH-UNIVASF 177- parent 1		Hybrid 1 (1×2)	Hybrid 3 (1×3)	Hybrid 5 (1×4)
BGH-UNIVASF 189 - parent 2	Hybrid 2 (2×1)		Hybrid 7 (2×3)	Hybrid 9 (2×4)
BGH-UNIVASF 67- parent 3	Hybrid 4 (3×1)	Hybrid 8 (3×2)		Hybrid 11 (3×4)
'Sugar Baby'- parent 4	Hybrid 6 (4×1)	Hybrid 10 (4×2)	Hybrid 12 (4×3)	

Watermelon seeds were sown in plastic trays with a commercial substrate based on organic compounds. Seedlings were transplanted when they had one to two true leaves, approximately 18 days after sowing, using a spacing of 3.0 m between rows and 0.8 m between plants. Plants were irrigated using a drip irrigation system with emitters spaced 0.3 m apart and a nominal flow rate of 2 L h⁻¹.

Pest control throughout the crop cycle consisted of application of alternative spray mixtures, including neem oil (*Azadirachta indica*) at 0.5%, Piretron (*Derris spp*) at 0.5%, and Dipel (*Bacillus thuringiensis*) at 1 g L⁻¹. Disease control consisted of application of a lime sulfur solution (a mixture of powdered sulfur and quicklime) at 0.5% to control powdery mildew (*Podosphaera xanthii*).

During flowering in the first evaluation year, controlled pollinations (self-pollinations) were performed to obtain segregating populations (F2) for all hybrid combinations. In the second evaluation year, fruit set occurred through open pollination, except for the parents BGH-UNIVASF 177 and BGH-UNIVASF 189, for which controlled pollinations (self-pollinations) were performed to maintain the seed stock of the respective accessions.

Fruits from self-pollination were harvested at commercial maturity, 30 to 35 days after pollination. For fruits from open pollination, maturity was determined based on morphological indicators, namely a woody sound when the fruit was tapped with the fingertips, drying of the tendril closest to the fruit, and a change in the color of the lower fruit surface in contact with the soil from white to yellow. After harvest, the fruits were transported to the Crop Science and Olericulture Laboratory (UNIVASF), where they were weighed and all fruit morphological analyses were performed.

The traits were evaluated as follows: earliness was determined by counting the days between transplanting and opening of the first female flower (DTF); mean fruit weight (MFW) was calculated as the ratio between the weight of all fruits produced in the plot and the number of fruits (kg); the mean number of fruits per plant (NFP) was determined as the quotient between the number of fruits produced in the plot and the number of plants; mean fruit production per plant (FPP) was determined as the weight of all fruits produced divided by the number of plants in the plot (kg plant⁻¹); and total fruit

yield (TFY) was estimated as the product of total fruit production per plant and the total number of plants per hectare (Mg ha⁻¹).

Mean marketable fruit weight (MMW), number of marketable fruits per plant (NMF), marketable fruit production per plant (MFP), and marketable fruit yield (MFY) were calculated using the same formulas as the corresponding variables related to total fruit yield, except that fruits weighing at least 3 kg were considered marketable. Plant vigor in the field and commercial attractiveness of the fruits at preharvest were also evaluated using a rating scale applied by at least three evaluators considering: general plant appearance (GPA), general fruit appearance (GFA), and general plant and fruit appearance (GPFA). For each variable, the rating scale was divided into not selected, assigned a score of zero (0); occasionally selected, assigned a score of one (1); and selected, assigned a score of two (2). Selected plants and fruits had good leaf cover and a more uniform appearance, respectively, and the fruits had no defects or malformations and were commercially attractive. Non-selected plants and fruits had traits opposite to those of selected plants and fruits, whereas occasionally selected plants and fruits had intermediate traits.

Fruit characterization consisted of selecting the most developed fruit from each plant and measuring its weight with a semi-analytical balance. In addition, fruit transverse diameter (FTD) and longitudinal diameter (FLD) were measured using a graduated ruler, and the longitudinal to transverse diameter ratio (FLD/FTD) was calculated. Peel thickness was determined in the peduncle, apex, sun-exposed side, and soil-contact side regions using a graduated ruler and their means were used to obtain the mean peel thickness (MPT). Soluble solids content (SSC, expressed in °Brix) was determined from homogenized pulp juice collected from the central-lateral region of the fruit using a portable manual refractometer.

The data were evaluated for ANOVA assumptions, including independence of observations, homogeneity of variances, and normality of group distributions, and variables that did not meet these assumptions were subjected to the following transformations: $\sqrt{x} + 1$ (DTF), $\log x + 0$ (MFW, TFY, MFP, MFY, and FLD), $\log x + 1$ (GPFA), $\sinh(\sqrt{x})$

(FPP). The variables FLD, MPT, and SSC did not meet the assumptions, even after the transformations were applied. Thus, the means obtained in the two experiments were subjected to diallel analysis according to the model of Griffing (1956), adopting method 1, as described by Cruz, Regazzi, and Carneiro (2012), using the Genes software for genetics and statistics (CRUZ, 2013).

RESULTS AND DISCUSSION

The general combining ability (GCA) effect was significant for earliness (DTF), fruit longitudinal diameter (FLD), longitudinal to transverse diameter ratio (FLD/FTD), and general plant appearance (GPA), indicating that at least one parent differed from the others in mean performance in the hybrid combinations (Table 4). These results may be associated with the inclusion of the cultivar 'Sugar Baby' as one of the parents because it has traits such as greater earliness, smaller fruit size, lower vegetative vigor, and high susceptibility to pests and diseases. Thus, significant GCA mean squares indicate differences among the GCA effects of the parental genotypes and the involvement of additive gene effects in the inheritance of these traits.

In the joint evaluation of the 17 variables, 14 variables were significant by the F test at the 5% probability level (data not shown), indicating genetic variability among the materials studied. Specific combining ability (SCA) effects were significant for DTF, fruit production per plant (FPP), total fruit yield (TFY), mean marketable fruit weight (MMW), FLD, and general fruit appearance (GFA). These results indicate that non-additive gene effects are involved in the control of these traits.

GCA and SCA effects were significant for DTF and FLD, indicating that additive and non-additive gene effects jointly controlled these traits. However, the values of the GCA quadratic components for DTF, FLD, FLD/FTD, mean peel thickness (MPT), soluble solids content (SSC), GPA, and general plant and fruit appearance (GPFA) were greater than those of the SCA quadratic components, indicating a predominance of additive gene effects for these traits (Table 4).

In contrast, the opposite pattern was observed for number of fruits per plant (NFP), mean fruit weight (MFW), FPP, TFY, number of marketable fruits per plant (NMF), MMW, marketable fruit production per plant (MFP), marketable fruit yield (MFY), FTD, and GFA, suggesting a predominance of non-additive gene effects in the control of these traits (Table 4). These results differ from those reported by Ferreira et al. (2002), who evaluated seven watermelon populations, their hybrids, and reciprocals and observed non-additive effects for DTF and SSC and additive effects for NFP and MFW.

These results are consistent with those reported by Souza, Gama, and Queiróz (2004), who evaluated the combining ability of two cultivars and one watermelon accession in a complete diallel and observed a predominance of non-additive effects for NFP, MFW, FPP, and FTD, whereas the opposite pattern was observed for DTF and SSC. Similarly, Sapovadiya et al. (2014) evaluated the combining ability of eight parents for four traits in a partial diallel and found a predominance of non-additive gene effects for NFP, MFW, and FPP, whereas additive gene effects predominated

for SSC. Similar results were also reported by Bahari et al. (2012), who evaluated four inbred lines, their F1 hybrids, and reciprocals in four different environments and concluded that additive gene effects predominated for DTF, SSC, NFP, MFW, and FPP, whereas non-additive gene effects predominated for MPT.

Differences among results from combining ability studies in watermelon may be due to different factors that, according to Gusmini and Wehner (2005), are related to the reduced number of parents and the nonrandom sampling procedure. For Souza, Gama, and Queiróz (2004), these differences may be attributed to the evaluated germplasm or to genotype $\times$ environment interaction. No significant reciprocal effects (R) were found for any of the traits evaluated, suggesting that extrachromosomal inheritance or maternal effects were not involved in the control of these traits.

These results contrast, to a greater or lesser degree, with those reported in the literature for diallel analysis studies in watermelon. In all studies, reciprocal effects were significant for a set of traits, with studies differing only in which traits showed evidence of extrachromosomal inheritance or maternal effects. Ferreira et al. (2002) evaluated a subset of the traits examined in this study and found significant reciprocal effects for DTF, MFW, and SSC, but not for NFP. Similarly, Souza, Gama, and Queiróz (2004) found significant reciprocal effects for DTF, NFP, and FPP, but not for MFW, FTD, FLD, and SSC. Nascimento et al. (2019) evaluated six parents of different origins, their hybrids, and reciprocals and observed significant reciprocal effects for DTF, MPT, and SSC, but not for MFW and NFP.

Based on the results obtained in this study and reports in the literature, each group of evaluated genotypes appears to have a specific genetic component, and maternal effects cannot be generalized to morphological traits of the female parent.

Regarding evaluation cycles (Y), no significant differences were detected for the evaluated variables, indicating that evaluation year did not influence the expression of the evaluated phenotypes. By contrast, significant genotype $\times$ year interaction ($G \times Y$) effects were found for FPP, TFY, NMF, MFP, MFY, FTD, FLD/FTD, SSC, and GPFA. These results may be associated with the higher incidence of aphids (*Aphis gossypii*), thrips (*Thrips tabaci*), and powdery mildew (*Podosphaera xanthii*) in the second evaluation year, with powdery mildew occurring during fruit development. Given the environmental influence on several traits, Gomes et al. (2020) emphasized the need to evaluate hybrid combinations in several locations to estimate GCA and SCA.

In addition, significant differences were found for the interaction between general combining ability and environment ($GCA \times Y$) for most evaluated traits, except MMW, FLD, FLD/FTD, and GPA, suggesting that the environment influenced the expression of additive genes for these traits. However, significant differences were detected for the interaction between specific combining ability and environment ($SCA \times Y$) only for FTD, FLD/FTD, and GPFA, indicating lower environmental influence on SCA for these variables. These results are similar to those reported by Bahari et al. (2012), who also did not find environmental influence on SCA for most evaluated variables.

Table 4. Joint analysis of variance for seventeen traits, evaluated in a diallel scheme, involving four watermelon parents.

Source of variation	Mean square									
	DF	DTF	NFP	MFW	FPP	TFY	NMF	MMW	MFP	MFY
Genotypes (G)	15	0.90	0.49	0.02	0.04	0.03	0.28	0.02	0.05	0.06
GCA	3	4.06*	0.23	0.04	0.06	0.04	0.29	0.02	0.08	0.09
SCA	6	0.13*	1.07	0.04	0.05*	0.04**	0.49	0.03**	0.09	0.09
Reciprocal (R)	6	0.08	0.03	0.00	0.01	0.01	0.06	0.01	0.01	0.01
Year (Y)	1	0.03	0.45	0.00	0.01	0.01	0.33	0.01	0.01	0.01
G × Y	15	0.05	0.33	0.01	0.03*	0.03**	0.32*	0.00	0.05**	0.05**
GCA × Y	3	0.15*	0.52*	0.02*	0.08**	0.10**	0.99**	0.01	0.15**	0.19**
SCA × Y	6	0.02	0.30	0.01	0.01	0.00	0.19	0.00	0.04	0.02
R × Y	6	0.02	0.26	0.00	0.02	0.01	0.11	0.00	0.01	0.01
Residue	72	0.04	0.18	0.01	0.01	0.01	0.16	0.00	0.02	0.02
Quadratic components										
GCA	0.083	-0.003	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.001
SCA	0.009	0.119	0.004	0.004	0.004	0.004	0.009	0.030	0.010	
Reciprocal	0.000	-0.027	-0.001	-0.001	-0.001	-0.021	0.000	-0.002	-0.002	
Source of variation	Mean square									
	DF	FTD	FLD ¹	FLD/FTD	MPT ¹	SSC ¹	GPA	GFA	GPFA	
Genotypes (G)	15	8.34	0.05*	0.78	0.14	2.22**	1.06	0.24	0.04	
GCA	3	21.68	0.18**	3.47**	0.28	8.04	4.74*	0.31	0.14	
SCA	6	8.35	0.02**	0.19	0.09	0.53	0.18	0.35*	0.02	
Reciprocal (R)	6	1.65	0.00	0.03	0.11	0.99	0.10	0.11	0.01	
Year (Y)	1	22.52	0.00	0.06	0.02	10.14	0.13	0.23	0.00	
G × Y	15	3.22*	0.00	0.05*	0.14	0.57**	0.13	0.11	0.01*	
GCA × Y	3	5.98**	0.00	0.02	0.44*	1.38**	0.17	0.35*	0.02*	
SCA × Y	6	3.30*	0.00	0.09**	0.09	0.18	0.17	0.05	0.01*	
R × Y	6	1.77	0.00	0.02	0.04	0.56*	0.06	0.05	0.00	
Residue	72	1.48	0.00	0.03	0.12	0.22	0.08	0.11	0.01	
Quadratic components										
GCA	0.390	0.004	0.071	0.001	0.158	0.096	0.002	0.003		
SCA	0.898	0.003	0.023	-0.026	0.016	0.005	0.022	0.002		
Reciprocal	-0.109	0.000	-0.001	-0.012	0.046	-0.004	-0.009	0.000		

¹Variables did not meet the assumptions of ANOVA. DTF = days between transplanting and opening of the first female flower; NFP = mean number of fruits per plant; MFW = mean fruit weight; FPP = mean fruit production per plant; TFY = total fruit yield; NMF = number of marketable fruits per plant; MMW = mean marketable fruit weight; MFP = marketable fruit production per plant; MFY = marketable fruit yield; FTD = fruit transverse diameter; FLD = longitudinal diameter; FLD/FTD = longitudinal to transverse diameter ratio; MPT = mean peel thickness; SSC = soluble solids content; GPA = general plant appearance; GFA = general fruit appearance; GPFA = general plant and fruit appearance.

When the interaction between reciprocal effects and environment (R × Y) was considered, significance was found only for SSC, indicating that parent performance as pollen donors or recipients was minimally influenced by environmental variation. In addition, this result may be directly associated with greater biotic pressure in the second evaluation year, probably influenced by favorable environmental factors such as temperature and humidity. This result is similar to that reported by Bahari et al. (2012), who detected an interaction between reciprocal effects and environment only for soluble solids content and number of days to fruit maturity.

Estimates of general combining ability effects (gij) provide information on the concentration of genes with predominantly additive effects and are important for identifying parents to be used in intrapopulation breeding programs (CRUZ; REGAZZI; CARNEIRO, 2012). In the mean GCA estimates for the 17 evaluated variables (Table 5), accession BGH-UNIVASF 177 (Gen. 1) showed positive effects for FPP, TFY, NMF, MFP, MFY, GPA, GPFA, MFW, MMW, FLD, and FLD/FTD and negative effects for DTF, for which positive values indicate later flowering, FTD, SSC, and GFA. Thus, this parent contributed to more productive progenies with larger and more elongated fruits, later

flowering, lower soluble solids content, and fruits less attractive to the consumer market.

For accession BGH-UNIVASF 189 (Gen. 2), positive GCA effects were found for NFP, FPP, TFY, NMF, MFP, MFY, GPA, GPFA, FLD/FTD, MPT, and SSC, and negative effects were found for DTF, MFW, MMW, FTD, FLD, and GFA, indicating that this genotype contributed mainly to prolific and more productive hybrids with good vegetative appearance, fruits with greater resistance to transport, and more rounded fruits, although with later flowering, lower fruit

weight, and lower attractiveness to the consumer market.

For accession BGH-UNIVASF 67 (Gen. 3), positive GCA effects were found for FPP, TFY, MFP, MFY, GPA, GPFA, MFW, MMW, FLD, FLD/FTD, MPT, and GFA, and negative effects were found for DTF, NFP, FTD, and SSC. This genotype therefore tended to contribute to progenies with high marketable yield, larger fruits, greater peel thickness, a more elongated shape, later flowering, fewer fruits per plant, and lower soluble solids content.

Table 5. Mean estimate of general combining ability (GCA) of four watermelon parents for 17 agronomic traits.

Traits	BGH-UNIVASF 177	BGH-UNIVASF 189	BGH-UNIVASF 67	'Sugar Baby'
DTF	1.037	1.906	2.075	-5.019
NFP	-0.006	0.100	-0.056	-0.037
FPP	0.303	0.347	0.172	-0.822
TFY	1.250	1.406	0.737	-3.394
NMF	0.034	0.066	0.016	-0.116
MFP	0.284	0.178	0.403	-0.866
MFY	1.172	0.697	1.722	-3.591
GPA	0.163	0.130	0.178	-0.470
GPFA	0.068	0.056	0.179	-0.303
MFW	0.156	-0.103	0.330	-0.384
MMW	0.118	-0.180	0.302	-0.240
FTD	-0.191	-0.409	-0.397	0.997
FLD	2.747	-0.153	3.297	-5.891
FLD/FTD	0.163	0.025	0.200	-0.388
MPT	0.009	0.022	0.072	-0.103
SSC	-0.312	0.100	-0.187	0.600
GFA	-0.064	-0.072	0.049	0.088

DTF = days between transplanting and opening of the first female flower; NFP = mean number of fruits per plant; MFW = mean fruit weight; FPP = mean fruit production per plant; TFY = total fruit yield; NMF = number of marketable fruits per plant; MMW = mean marketable fruit weight; MFP = marketable fruit production per plant; MFY = marketable fruit yield; FTD = fruit transverse diameter; FLD = longitudinal diameter; FLD/FTD = longitudinal to transverse diameter ratio; MPT = mean peel thickness; SSC = soluble solids content; GPA = general plant appearance; GFA = general fruit appearance; GPFA = general plant and fruit appearance.

The cultivar 'Sugar Baby' (Gen. 4) showed negative effects for most variables, except FTD, SSC, and GFA, indicating that crosses involving this cultivar were associated with earlier genotypes, fruits with higher soluble solids content, a more rounded shape, higher pulp yield, and greater attractiveness to the consumer market. However, this cultivar was associated with lower fruit weight, fewer fruits per plant, lower yield, poor vegetative development, and lower acceptability when the plant–fruit set was evaluated.

Accessions BGH-UNIVASF 189 (Gen. 2) and BGH-UNIVASF 177 (Gen. 1) were the parents with the greatest contributions to variables related to total production yield (FPP and TFY). However, when fruits weighing at least 3 kg were considered, the parents BGH-UNIVASF 177 (Gen. 1) and BGH-UNIVASF 67 (Gen. 3) had the greatest contributions to MFP, MFY, MFW, and MMW. SCA effects were analyzed from two perspectives: effects resulting from crosses of each parent with itself (Sii; Table 6), and effects resulting from crosses with other parents (Sij; Tables 7 and 8).

According to Cruz and Vencovsky (1989), analysis of Sii effects is an important indicator of the presence or absence of unidirectional dominance. When Sii values are negative, dominance deviations are predominantly positive, and vice versa. In addition, the closer Sii is to zero, the lower the divergence and heterosis in the hybrids. Thus, negative Sii effects were found for most parents for NFP, FPP, TFY, NMF, MFP, MFY, GPFA, FTD, MPT, SSC, and GFA, indicating unidirectional dominance deviations with positive heterosis in hybrid combinations between divergent parents (Table 6). In contrast, positive Sii effects were observed for most parents for DTF and FLD/FTD, suggesting negative heterosis.

Each parent had greater divergence for a specific group of variables, especially 'Sugar Baby' (Gen. 4) and accession BGH-UNIVASF 67 (Gen. 3) (Table 6). However, although the magnitude of this parameter results in greater heterosis in the hybrids, identification of the most promising hybrids is directly related to the best performance of their parents, in

terms of GCA, for each trait (CRUZ; REGAZZI; CARNEIRO, 2012). Mean SCA estimates were obtained from crosses between different parents (Sij) (Tables 7 and 8). These estimates express the contribution of genes with non-additive

effects and represent deviations in hybrid performance from what would be expected based on the GCA of their parents (CRUZ; REGAZZI; CARNEIRO, 2012).

Table 6. Mean estimates of specific combining ability (SCA; effects resulting from crosses of each parent with itself – Sii) for 17 traits in four watermelon parents grown in an agroecological production system.

Traits	BGH-UNIVASF 177	BGH-UNIVASF 189	BGH-UNIVASF 67	'Sugar Baby'
DTF	2.231	1.744	1.306	2.194
NFP	-0.369	-0.231	0.581	-0.106
FPP	-1.697	-1.034	0.416	-1.897
TFY	-7.031	-4.244	1.694	-7.744
NMF	-0.228	-0.241	0.259	-0.278
MFP	-1.378	-0.866	-0.366	-2.478
MFY	-5.597	-3.547	-1.547	-10.272
GPA	0.097	-0.212	-0.043	0.108
GPFA	-0.041	-0.292	-0.214	-0.221
MFW	0.118	0.041	-1.334	-0.827
MMW	0.055	0.285	-1.300	-0.820
FTD	-0.866	-0.728	-0.853	-1.891
FLD	2.347	-0.953	-4.703	0.172
FLD/FTD	0.213	0.038	-0.162	0.163
MPT	0.084	-0.091	-0.141	-0.041
SSC	-0.113	-0.338	0.237	-0.138
GFA	-0.204	-0.259	-0.301	-0.218

Thus, F1 hybrids with low Sij values perform as expected based on the general combining ability (GCA) of their parents; by contrast, higher absolute Sij values indicate that the performance of a specific cross is relatively better or worse than expected based on parental GCA (CRUZ; REGAZZI; CARNEIRO, 2012). Furthermore, the most promising hybrid has the highest SCA estimate, either negative or positive depending on the trait analyzed, divergent parents, and at least one parent with high GCA (CRUZ; REGAZZI; CARNEIRO, 2012).

Therefore, considering the full set of analyzed variables, hybrid 11 (3×4) was the most promising because its SCA estimates were the best and were consistent with the GCA of its parents for most variables (DTF, FPP, TFY, MFP, MFY, GPFA, MFW, MMW, FTD, FLD, MPT, and GFA) (Tables 7 and 8). Therefore, this hybrid was promising for agronomically important traits, such as earliness, fruit yield, and fruit size, as larger fruits are still more valued in the domestic market.

Breeding programs focus on combining the greatest number of desirable agronomic traits accepted by the consumer market. Consumer preference is important in the selection of watermelon genotypes, mainly for fruit size and shape. Although larger fruits are still more valued in the domestic market, the consumer demand has been changing for increasingly smaller watermelons to meet family needs and avoid waste (COSTA et al., 2013). This demand is already a reality in the export market.

In this context, hybrids 5 (1×4) and 9 (2×4) combined

highly desirable traits because they had early and more productive plants with smaller and more rounded fruits. Hybrid 9 had high values for NFP, FPP, TFY, NMF, MFP, MFY, and GPA, whereas hybrid 5 (1×4) had the highest SCA values for FPP, TFY, NMF, MFP, MFY, FTD, and SSC. In addition, both hybrids had low SCA values for DTF, MPT, FLD, and MMW, consistent with the GCA of at least one of their parents.

Hybrid 1 (1×2) was also among the best hybrids, with the highest SCA values for NFP, FPP, TFY, NMF, MFP, MFY, GPA, and SSC and the lowest SCA value for MFW. One parent had GCA values consistent with all the traits mentioned. Thus, this hybrid had a highly favorable trait set for developing high-yielding materials with good vegetative development, higher soluble solids content, and smaller fruit size. As demonstrated in the joint analysis of variance, reciprocal effects were not significant for any variable, indicating that the parents selected as the most promising can be used as either pollen donors or recipients. This is advantageous because it facilitates field management of these parents.

These results indicate that, depending on the breeder's objectives, hybrid combinations 1 (1×2), 5 (1×4), 9 (2×4), and 11 (3×4) have substantial potential for continuation of the watermelon breeding process in an agroecological system. These hybrid combinations can be used in breeding programs to obtain lines for subsequent development of cultivars (open-pollinated varieties or hybrids), because additive and non-additive variability was found for the evaluated traits. The

general and specific combining ability results indicate the potential of crosses among all parents involved, specifically BGH-UNIVASF 67 (Gen. 3) $\times$ 'Sugar Baby' (Gen. 4), BGH-UNIVASF 177 (Gen. 1) $\times$ BGH-UNIVASF 189 (Gen. 2),

BGH-UNIVASF 177 (Gen. 1) $\times$ 'Sugar Baby' (Gen. 4), and BGH-UNIVASF 189 (Gen. 2) $\times$ 'Sugar Baby' (Gen. 4), as base materials for developing segregating populations.

Table 7. Mean estimates of specific combining ability (SCA; effects resulting from crosses with other parents – S_{ij}) for plant and yield traits in watermelon hybrids.

Traits	Crosses					
	1(1 $\times$ 2)	3 (1 $\times$ 3)	5 (1 $\times$ 4)	7 (2 $\times$ 3)	9 (2 $\times$ 4)	11 (3 $\times$ 4)
DTF	-0.912	-0.981	-0.337	0.350	-1.181	-0.675
NFP	0.275	-0.119	0.213	-0.200	0.156	-0.263
FPP	1.059	-0.091	0.728	-0.759	0.734	0.434
TFY	4.413	-0.394	3.013	-3.100	2.931	1.800
NMF	0.141	-0.084	0.172	-0.091	0.191	-0.084
MFP	0.803	-0.122	0.697	-0.616	0.678	1.103
MFY	3.228	-0.547	2.916	-2.472	2.791	4.566
GPA	0.095	0.009	-0.200	0.030	0.088	0.005
GPFA	0.079	0.052	-0.091	0.032	0.181	0.130

Table 8. Mean estimates of specific combining ability (SCA; effects resulting from crosses with other parents – S_{ij}) for fruit traits in watermelon hybrids.

Traits	Crosses					
	1(1 $\times$ 2)	3 (1 $\times$ 3)	5 (1 $\times$ 4)	7 (2 $\times$ 3)	9 (2 $\times$ 4)	11 (3 $\times$ 4)
MFW	-0.193	0.247	-0.172	0.121	0.032	0.967
MMW	0.012	0.165	-0.233	-0.108	-0.190	1.243
FTD	0.303	-0.009	0.572	-0.016	0.441	0.878
FLD	-0.603	0.497	-2.241	1.847	-0.291	2.359
FLD/FTD	-0.075	0.025	-0.162	0.088	-0.050	0.050
MPT	0.047	-0.053	-0.078	0.059	-0.016	0.134
SSC	0.300	-0.263	0.075	0.000	0.037	0.025
GFA	0.116	0.082	0.006	0.075	0.069	0.143

Most (58.8%) of the analyzed variables were controlled by non-additive gene effects; thus, an interpopulation breeding strategy based on heterosis exploitation may provide greater gains than an intrapopulation breeding strategy (AMARAL JÚNIOR et al., 1996). For this purpose, reciprocal recurrent selection can be applied (BORÉM; MIRANDA, 2009). Conversely, for traits in which additive gene effects predominated (41.2%), intrapopulation breeding methods are the most appropriate strategy (AMARAL JÚNIOR et al., 1996).

In this case, the pedigree method can be applied to fix desirable traits in lines because watermelon has good tolerance to inbreeding; recurrent selection among inbred progenies can also be applied to increase genetic gains at the intrapopulation level. Alternatively, reciprocal recurrent selection among interpopulation full-sib progenies can be applied, as reported by Borém and Miranda (2009); this approach corresponds to the cryptic hybrid method proposed by Paterniani and Miranda Filho (1978) and cited by Souza, Gama, and Queiróz (2004), which enables simultaneous use

of combining ability effects governed by additive and non-additive gene action.

In addition to these technical aspects, the strategy used must be directly related to the type of material to be developed, open-pollinated varieties or hybrids, and to the economic capacity of farmers. In this regard, intrapopulation breeding methods aimed at obtaining lines for the subsequent development of open-pollinated varieties would be more appropriate for family farmers when used within a participatory breeding approach. In this method, productivity gains are pursued while biodiversity conservation and enhancement, acquisition and use of locally adapted germplasm, selection within populations, experimental evaluation of varieties, release and dissemination of new varieties, diversification of the production system, and seed production are promoted (MACHADO, 2014). Conversely, interpopulation breeding methods aimed at obtaining hybrids would be more appropriate for export-oriented growers who produce this crop at a more intensive technological level and with greater economic capacity.

CONCLUSIONS

Based on general combining ability (GCA), the genotypes BGH-UNIVASF 177 and BGH-UNIVASF 67 were promising for obtaining marketable fruits with higher yield and greater weight when grown in sustainability-based environments. The cultivar ‘Sugar Baby’ was identified as a good combiner for earliness, fruit diameter, and soluble solids content, whereas the parent BGH-UNIVASF 189 was identified as a good combiner for total fruit yield and soluble solids content.

Based on specific combining ability (SCA), hybrid 11 (3×4) was the most promising for the greatest number of agronomically important traits, with potential for developing genotypes with greater earliness, higher yield, greater weight, and more attractive fruit and plant–fruit appearance. Hybrids 1 (1×2), 5 (1×4), and 9 (2×4) were also promising for earliness, higher soluble solids content, higher fruit yield, good vegetative development, and lower fruit weight.

No reciprocal effects were found for the traits evaluated.

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