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ORIGINAL RESEARCH ARTICLE

Combining ability of carrot genitors for root yield traits and leaf blight tolerance

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ABSTRACT

The market demand for uniformity and productivity of commercial carrot roots has prioritized hybrid materials over open-pollinated varieties. In this sense, the objective of this work was to estimate the combining ability of carrot genitors for root productivity and resistance to leaf scorch. The experiments were conducted in Gama, DF, in the agricultural years 2012/13 and 2013/14. We evaluated 33 carrot hybrids, originated from crosses between three male-sterile populations, with 11 male-fertile S2 lines, all the genitors being of tropical origin. At 90 days after sowing, the severity of the leaf blight disease was estimated in the plots. At 100 days after sowing, harvesting was performed and root yield characters were evaluated. Analysis of variance and partial diallel analysis were performed for each year and jointly for both years. It was found that additive and non-additive genes are important in the manifestation of root yield and leaf blight resistance traits in carrot hybrids. The male-sterile parents with higher overall combining ability for root productivity are strains LM-649 and LM-650 and, among the male-fertile, strain LM-555-2-2. The best hybrids for root yield and leaf blight resistance are LM-649 × LM-555-11-1, LM-650 × LM-555-7-1 and LM-650 × LM-554-8-1.

Keywords: *Daucus carota* L.; Hybrids; Partial Diallel Analysis

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1. Introduction

In the early 1980s, the carrot cultivar Brasilia (*Daucus carota* L.) was released by Embrapa[1], which came to occupy more than 80% of the area cultivated with summer carrots in Brazil[2]. This success was due to the high productivity of Brasília and especially the resistance to leaf blight (a disease caused by the complex *Alternaria dauci* (Kühn) Groves & Sholko, *Cercospora carotae* (Passerini) Solheim and *Xanthomonas campestris* (Pam.) Dows. pv. *carotae* Kendr), considered worldwide the main disease of carrots in summer crops[3].

However, due to the current demand for hybrid cultivars in the seed market, the marketing of seeds of open-pollinated cultivars, such as those released by Embrapa, has been replaced by hybrids. This demand is due to the greater uniformity of roots of hybrids and, consequently, the higher yield of commercial roots[4,5].

In view of this trend, the genetic improvement programs of carrots, which initially worked on the development of open-pollinated cultivars, initiated programs aimed at obtaining hybrid seeds, which also occurred at Embrapa. Obtaining carrot hybrids on a commercial scale was only possible after the discovery of male-sterility, called "brown", which enabled the crossing between distinct strains[6].

For the selection of parent lines, one of the most efficient methodologies commonly used in breeding programs is diallel analysis, which provides estimates of genetic parameters, useful for the selection of parents to be used in hybridization and in understanding the gene action involved in the determination of traits and the existence of heterosis, thus providing great advances for selection[7]. Among the various methods proposed for the analysis of diallel crosses, Griffing's method[8] has been widely used. This method provides information about the general combining ability of the parents (GCA), which is related to the concentration of predominantly additive genes, and the specific combining ability (SCA), related to the concentration of genes with basically non-additive effects (dominance and epistasis)[9].

The difficulty of studying a large number of parents in complete dialogues has led to the development of adaptations, such as partial dialogues. These adaptations involve the evaluation of genitors arranged in two groups, belonging or not to a common set, with inferences being made for each group[7].

Few studies published in the literature present estimates of combinatorial ability in carrots. However, some studies have shown the existence of heterosis and the efficiency of using diallel analysis to choose genitors and superior hybrid combinations[10–14].

Given the above, the objective of this work was to estimate the combining ability, identifying the best carrot genitors for root yield and leaf blight tolerance traits.

2. Material and methods

The experiments were conducted in Gama, DF, in the 2012/13 and 2013/14 agricultural years. We evaluated 33 carrot hybrids, originating from controlled crosses between two groups of parents, in a partial diallel model (3 × 11), according to the "experiment 2" model of Comstock & Robinson[15]. This model involves the evaluation of genitors arranged in two groups, belonging or not to a common set[7]. The genitors in group I were the male-fertile strains named LM-633, LM-649 and LM-650, while group II was composed of the male-fertile genitors: LM-555-13-1, LM-555-2-2, LM-555-7-1, LM-555-2-1, LM-555-60-1, LM-554-8-1, LM-570-34-1, LM-588-11-1, LM-555-29-2, LM-588-11-4, LM-555-59-3, both groups being of tropical origin.

In the 2012/13 crop year, the 33 hybrids were grown in an augmented block design and three witness cultivars, coincident in each repetition, Brasilia, Juliana F_1 and BRS Planalto. Sowing was performed on 11/18/2012. The use of this design was due to the small quantity of seeds available. In the 2013/14 crop year, the hybrids were grown in randomized block design, with three repetitions, and sowing was performed on 12/11/2013.

For the experiments, the soil was conventionally prepared with plowing and harrowing. Then, 1.0 m wide beds were suspended and fertilized with 1,200 kg ha^{-1} of the commercial formula (N-P-K) 04-30-16, plus boron and zinc. A rotary tiller was used to incorporate the fertilizer into the beds. In both experiments, sowing was performed in furrows made in the transversal direction of the beds, at double spacing, with single row spacing of 10 cm and double row spacing of 20 cm, with four double rows in each plot. The plots measured 1.2 m^2. The cultural treatments of the experiments were performed according to Filgueira[16]. Weeds were controlled by applying linuron herbicide at a dose of 0.99 L i.a. $ha^{-1,}$ four days after sowing. The thinning of the plants was performed 30 days after sowing, leaving an approximate spacing of 5 cm between plants. Next, a covering fertilization was performed, with application of 400 kg ha^{-1} of ammonium sulfate (N = 20%). Supplemental irrigation, when necessary, was performed by conventional sprinkling until the soil reached field capacity. No fungicides or bactericides were used for disease control.

At 90 days after sowing, the severity of leaf blight was evaluated in the plots, and at 100 days, the harvest was performed and the characters total number of roots in the plot (NTR), total mass of roots in the plot (MTR), number of marketable roots per plot (NRC), mass of marketable roots per plot (MRC) were evaluated. Roots with at least 2.5 cm in diameter and 14 cm in length were considered marketable. The characters MTR and MRC were transformed to t ha^{-1}.

The data were confirmed for normality of distribution (Lilliefors test)[17] and homogeneity of variance (Bartllet test)[18] of errors. Subsequently, variance and partial dialectic analyses were performed for each year and jointly for both years.

Analyses were performed with the program GENES VS. 2013.5.1[19].

3. Results and discussion

The partial diallel analyses of variance revealed significant differences ($p < 0.05$) for all characters, between hybrids and cultivars in crop years 2012/13, and between hybrids in 2013/14 (**Table 1**). There was significant interaction between genotypes and years and interaction between general combining ability (GCA) and specific combining ability (SCA) with crop years, for all characters.

Root yields were higher in 2013/14 compared to 2012/13 (**Table 1**). In 2012/13, when control cultivars were used, on average, the root yields of the hybrids were similar to those of the cultivars Juliana F_1 and BRS Planalto, and higher than those of the cultivar Brasilia. As for leaf blight, the hybrids, on average, were more tolerant than cultivars Juliana F_1 and Brasília and similar to BRS Planalto. The average marketable root yield of the hybrids ranged from 24.26 to 38.43 t ha^{-1}, in both years, while total root yield ranged from 33.26 to 48.81 t ha^{-1}; mean severity for leaf-burn ranged from 16.77 to 29.18%. Carvalho *et al.*[14] evaluated hybrids obtained from temperate and tropical strains and found higher root yields than those obtained in this work, with 40.58 t ha^{-1} of marketable roots and 55.63 t ha^{-1} of total root yield; as for leaf blight, the average severity was similar, 28.32%. These root yield values are higher than the national average, which is 29.43 t ha^{-1}[20], while in regions that use hybrids and large amounts of inputs, mainly fertilizers, agrochemicals and supplemental irrigation by central pivot, in practically 100% of the area, as in São Gotardo-MG and Criatalina-GO, yields can reach 100 t ha^{-1} in winter crops[21].

Table 1. Mean squares of the diallel analysis of variance of carrot genitors, for root yield and leaf blight tolerance traits, evaluated in the 2012/13 and 2013/14 agricultural years, Brasilia, 2014

FV	GL	NRC	MRC	NTR	MTR	QDF
2012/13						
Genotypes	32	203.18*	90.18*	837.87*	132.78*	454.48*
CGC-group I	2	94.18*	76.23*	1,490.27*	6.69*	1,046.13*
CGC-group II	10	365.20*	164.75*	946.60*	220.59*	393.61*
CEC	20	133.08*	54.29*	718.27*	101.47*	426.25*
Average of hybrids	-	35.33	24.26	70.33	33.26	29.18
Brasilia Average	-	22.78	14.11	69.11	23.86	46.11
Average Juliana F_1	-	33.89	21.68	69.89	32.12	50.70
Average BRS Planalto	-	30.44	24.10	69.56	32.95	30.32
2013/14						
Genotypes	32	125.95*	54.00*	604.08*	72.88*	195.17*
CGC-group I	2	42.88*	10.30*	1,306.44*	1.90	198.83*
CGC-group II	10	79.22*	35.85*	392.36*	50.75*	271.54*
CEC	20	157.63*	67.44*	639.70*	91.04*	156.61*
Average of hybrids	-	67.23	38.43	108.78	48.81	16.77
Joint						
Genotype × year	32	165.29*	77.85*	607.24*	103.65*	211.08*
CGC-group I × year	2	80.40*	24.78*	1172.56*	7.73*	559.62*
CGC-group II × year	10	221.50*	98.63*	541.72*	103.69*	239.88*
CEC × year	20	145.67*	72.76*	583.46*	113.22*	161.83*

NRC: number of marketable roots per plot; MRC: mass of marketable roots t ha^{-1}; NTR: total number of roots per plot; MTR: total root mass t ha^{-1}; QDF: leaf-burn severity. CGC: general combining ability; CEC: specific combining ability.
*Significant difference by the F test at 5% probability.

In the set of characters evaluated, considering both years, it was found that the effects of CGC and CEC were significant for most characters. The only exception was for the CGC of genotype group I for the character total root productivity (TTP) in 2013/14 (**Table 1**). In the observation of the magnitude of the mean squares, it can be seen that there is no predominance of CGC or CEC effects in the different years, that is, both effects were important.

Simon & Strandberg[11] evaluated five divergent lines widely used in US carrot breeding programs for tolerance to alternaria leaf blight and found a predominance of additive effects to control this character, but with some dominance effects. Carvalho *et al.*[14] evaluated hybrids obtained by crossing lines of tropical and temperate origin and found a predominance of non-additive effects for leaf blight.

Regarding root productivity, Duan *et al.*[10] and Guan *et al.*[12] found heterosis effects and predominance of CGC effects, in work performed with carrot hybrids, although dominance effects (CEC) also contributed significantly to root productivity of most hybrid combinations. Jagosz[13], studying European strains, found a predominance of additive effects for total root productivity, and non-additive effects for marketable root productivity. Carvalho *et al.*[14] found a predominance of additive effects in the expression of root productivity traits. Considering the lack of a standard among the literature, the results obtained in this study and in the work of Carvalho *et al.*[14], who used lines of temperate and tropical origins, suggest that the predominance of additive or non-additive gene action in carrot hybrids is specific to the heterotic groups evaluated.

Table 2. General combining ability of carrot genitors, for root yield and leaf-burn tolerance characters, evaluated in the 2012/13 and 2013/14 agricultural years, Brasilia, 2014

Parent	Characters				
Group I 2012/13					
	NRC	MRC	NTR	MTR	QDF
LM-633	-1.88	-0.80	-1.97	-0.52	-5.94
LM-649	1.39	1.75	-5.52	0.32	0.68
LM-650	0.49	-0.95	7.49	0.19	5.26
Group I 2013/14					
LM-633	-0.11	-0.63	6.64	0.25^{ns}	0.78
LM-649	-1.08	0.45	-5.88	-0.22^{ns}	-2.75
LM-650	1.19	0.18	-0.76	-0.03^{ns}	1.97
Group II 2012/13					
LM-555-13-1	11.67	4.02	17.00	5.52	-1.78
LM-555-2-2	4.67	4.76	-6.67	1.10	-1.78
LM-555-7-1	-2.33	-4.47	0.33	-4.02	4.68
LM-555-2-1	-4.00	-2.49	-8.00	-3.82	4.68
LM-555-60-1	-8.33	-5.42	-9.00	-5.28	2.07
LM-554-8-1	1.00	3.11	0.67	3.32	8.53
LM-570-34-1	-8.33	-5.47	-18.67	-7.95	8.53
LM-588-11-1	1.00	-1.40	2.33	-1.68	0.84
LM-555-29-2	8.33	6.18	13.33	6.80	-10.69
LM-588-11-4	0.33	2.63	3.00	5.60	-9.47
LM-555-59-3	-4.00	-1.46	5.67	0.41	-5.62
Group II 2013/14					
LM-555-13-1	2.22	-1.59	3.10	-0.85	7.41
LM-555-2-2	2.66	2.16	-3.12	1.43	1.17
LM-555-7-1	-2.34	-3.28	-1.79	-3.80	2.69
LM-555-2-1	-5.24	-1.20	-7.56	-2.18	-2.92
LM-555-60-1	0.32	0.22	1.55	-0.22	10.22
LM-554-8-1	-2.68	1.33	-12.57	3.38	1.80
LM-570-34-1	1.99	3.23	4.99	1.74	-1.88
LM-588-11-1	1.22	-1.19	2.10	-3.54	-7.98
LM-555-29-2	-3.79	-1.80	4.66	0.77	-4.69
LM-588-11-4	2.55	1.86	-3.01	0.78	-5.72
LM-555-59-3	3.10	0.28	11.66	2.49	-0.11

NRC: number of marketable roots per plot; MRC: mass of marketable roots t ha^{-1}; NTR: total number of roots per plot; MTR: total root mass t ha^{-1}; QDF: leaf-burn severity.

Regarding the CGC of the group I of genotypes, male-sterile lines, observing the estimates that were repeated in both years, it can be seen that strain LM-649 was superior to the others for most root productivity characters, contributing additive genes mainly for mass of marketable roots (MRC) and total roots (MTR), while strain LM-650 showed higher CGC for number of marketable roots (NRC) and strain LM-633 did not show stable performance in both years (**Table 2**). For leafhopper tolerance, in which negative values of combining ability are preferred, it was observed that strain LM-633 was superior in 2012/13 and, LM-649 in 2013/14, while strain LM-650 showed the worst performance (**Ta-**

ble 2).

The genetic variability between strains of temperate origin was studied by Simon & Strandberg[11]. These authors found highly significant differences between them and concluded that the strains could contribute differently, in hybrids, to greater or lesser tolerance to leaf blight. The same was observed by Carvalho *et al.*[14], who found great variability for tolerance to leaf blight, without temperate genitors, some contributing to the improvement of the character. Regarding the selection of genitors more tolerant to leaf blight for the production of summer hybrids, this trait should be considered, because, according to Brito *et al.*[22] and Pereira *et al.*[22], defoliation caused by the disease is reflected in lower productivity and root quality.

The highest and most stable CGC for the genotypes in group II, male-fertile lines, for root yield characters were obtained by strain LM-555-2-2, which showed inferior performance only in relation to the total number of roots per plot (**Table 2**); similarly, strains LM-554-8-1 and LM-588-11-4 also showed higher CGC for mass of marketable roots (MRC). For leaf-burn tolerance, the highest negative values for CGC were obtained by strains LM-555-29-2, LM-588-11-4 and LM-555-59-3. It is observed, therefore, that it was not possible to identify strains, in group II, that contribute with desirable CGC for both root yield and leaf blight tolerance traits, indicating that crosses between genotypes of the two groups should be tried, seeking to combine high root yield and tolerance to the disease.

Observing the estimates of specific combining ability, which were more stable in the years 2012/13 (**Table 3**) and 2013/14 (**Table 4**), it can be seen that for the marketable root characters, the crosses LM-649 × LM-555-2-1, LM-649 × LM-555-59-3,

Table 3. Specific combining ability of carrot genitors, for root yield characters and leaf blight tolerance, evaluated in the crop year 2012/13, Brasília, 2014

Hybrids	NRC	MRC	NTR	MTR	QDF
LM-633 × LM-555-13-1	3.88	5.25	6.64	8.27	9.79
LM-633 × LM-555-2-2-	5.88	4.78	12.30	7.03	9.79
LM-633 × LM-555-7-1	2.88	-0.26	5.30	1.00	3.33
LM-633 × LM-555-2-1	-5.46	-2.31	-11.36	-4.00	-8.21
LM-633 × LM-555-60-1	-6.12	-2.17	-22.36	-6.00	5.94
LM-633 × LM-554-8-1	-4.46	-5.70	13.97	-1.80	18.86
LM-633 × LM-570-34-1	-2.12	-0.40	-12.70	-3.53	-0.52
LM-633 × LM-588-11-1	-5.46	-2.26	-6.70	-4.07	-15.90
LM-633 × LM-555-29-2	10.21	5.43	8.30	3.98	-8.05
LM-633 × LM-588-11-4	-1.79	-3.22	1.64	-2.22	-5.59
LM-633 × LM-555-59-3	2.55	0.87	4.97	1.32	-9.44
LM-649 × LM-555-13-1	-4.39	-6.11	-11.82	-7.10	-8.38
LM-649 × LM-555-2-2	0.61	-0.58	1.85	-1.01	-8.38
LM-649 × LM-555-7-1	-5.39	-2.82	-4.15	-1.97	16.08
LM-649 × LM-555-2-1	9.27	3.67	30.18	8.04	-3.30
LM-649 × LM-555-60-1	-1.39	0.47	3.18	2.37	-0.68
LM-649 × LM-554-8-1	-5.73	0.80	-25.49	-4.43	-7.14
LM-649 × LM-570-34-1	3.61	0.58	8.85	-0.10	-7.14
LM-649 × LM-588-11-1	8.27	4.85	10.85	5.37	0.55
LM-649 × LM-555-29-2	-3.06	-2.93	2.85	-1.26	12.08
LM-649 × 588-11-4	-3.06	-1.64	-11.82	-5.06	-0.69
LM-649 × LM-555-59-3	1.27	3.71	-4.49	5.14	7.01
LM-650 × LM-555-13-1	0.52	0.86	5.18	-1.17	-1.41
LM-650 × LM-555-2-2	-6.49	-4.20	-14.15	-6.02	-1.41
LM-650 × LM-555-7-1	2.52	3.08	-1.15	0.96	-19.41
LM-650 × LM-555-2-1	-3.82	-1.36	-18.82	-4.04	11.51
LM-650 × LM-555-60-1	7.52	1.70	19.18	3.63	-5.26
LM-650 × LM-554-8-1	10.18	4.90	11.52	6.23	-11.72
LM-650 × LM-570-34-1	-1.49	-0.18	3.85	3.63	7.66
LM-650 × LM-588-11-1	-2.82	-2.59	-4.15	-1.30	15.35
LM-650 × LM-555-29-2	-7.15	-2.50	-11.15	-2.73	-4.03
LM-650 × LM-588-11-4	4.85	4.86	10.18	7.27	6.28
LM-650 × 555-59-3	-3.82	-4.58	-0.49	-6.46	2.43

NRC: number of marketable roots per plot; MRC: mass of marketable roots t ha^{-1}; NTR: total number of roots per plot; MTR: total root mass t ha^{-1}; QDF: leaf-burning severity.

Table 4. Specific combining ability of carrot genitors, for root yield characters and leaf blight tolerance, evaluated in the 2013/14 crop year, Brasília, 2014

Hybrids	NRC	MRC	NTR	MTR	QDF
LM-633 × LM-555-13-1	-4.67	-0.48	-16.19	-3.34	-2.14
LM-633 × LM-555-2-2	-4.78	-6.04	3.36	-5.27	8.67
LM-633 × LM-555-7-1	-0.78	0.93	-11.31	-0.61	-0.54
LM-633 × LM-555-2-1	5.45	-1.03	14.81	-3.66	5.07
LM-633 × LM-555-60-1	5.56	10.36	1.36	10.17	-0.38
LM-633 × LM-554-8-1	10.89	0.49	25.14	7.65	14.50
LM-633 × LM-570-34-1	2.89	3.10	8.59	3.15	-9.69
LM-633 × LM-588-11-1	-5.67	0.64	-7.52	1.50	-5.78
LM-633 × LM-555-29-2	-7.66	-5.96	-14.75	-7.56	-6.15
LM-633 × LM-588-11-4	3.67	3.04	9.92	3.08	-5.84
LM-633 × LM-555-59-3	-4.89	-5.03	-13.41	-5.10	2.27
LM-649 × LM-555-13-1	1.63	-2.56	9.32	2.04	-5.57
LM-649 × LM-555-2-2	-1.14	2.23	-12.12	2.43	-0.05
LM-649 × LM-555-7-1	-5.14	-3.43	4.55	-2.34	2.26
LM-649 × LM-555-2-1	4.41	3.61	-2.34	4.96	-4.39
LM-649 × LM-555-60-1	-6.14	-5.52	7.22	-3.57	-0.68
LM-649 × LM-554-8-1	-11.14	-3.19	-25.01	-9.14	-9.83
LM-649 × LM-570-34-1	5.53	-1.24	5.43	-1.96	2.99
LM-649 × LM-588-11-1	4.30	-0.96	12.32	0.22	5.25
LM-649 × LM-555-29-2	10.97	5.64	13.44	4.44	9.64
LM-649 × LM-588-11-4	-5.70	-0.39	-17.57	-3.14	2.99
LM-649 × LM-555-59-3	2.42	5.79	4.77	6.04	-2.62
LM-650 × LM-555-13-1	3.03	3.04	6.87	1.30	7.71
LM-650 × LM-555-2-2	5.92	3.81	8.76	2.84	-8.62
LM-650 × LM-555-7-1	5.92	2.50	6.76	2.95	-1.72
LM-650 × LM-555-2-1	-9.86	-2.57	-12.47	-1.30	-0.68
LM-650 × LM-555-60-1	0.59	-4.84	-8.58	-6.60	1.06
LM-650 × LM-554-8-1	0.26	2.70	-0.13	1.49	-4.67
LM-650 × LM-570-34-1	-8.42	-1.86	-14.02	-1.19	6.70
LM-650 × LM-588-11-1	1.36	0.32	-4.80	-1.72	0.53
LM-650 × LM-555-29-2	-3.31	0.32	1.31	3.12	-3.49
LM-650 × LM-588-11-4	2.03	-2.65	7.65	0.06	2.85
LM-650 × LM-555-59-3	2.48	-0.76	8.64	-0.94	0.35

NRC: number of marketable roots per plot; MRC: mass of marketable roots t ha^{-1}; NTR: total number of roots per plot; MTR: total root mass t ha^{-1}; QDF: leaf-burn severity.

LM-650 × LM-555-7-1 and LM-650 × LM-554-8-1 were superior to the others. For the recommendation of a cross, it is necessary that at least one of the genitors present high CGC[7]. Both strains in group I, contained in these crosses, were also better for these characters in relation to CGC, while for group II, only strain LM-554-8-1 showed higher CGC for PRC. These results of the specific combinations indicate that there was gene complementarity in these crosses, caused by additive genes and also by non-additive genes, agreeing with the ratios of the mean squares observed in **Table 1**.

For the MTR character, the crosses LM-649 × LM-588-11-1 and LM-650 × LM- 588-11-4 stood out for both years (**Tables 3** and **4**). The group I lines involved in these crosses showed positive CGC values for MTR in 2012/13, whereas, in 2013/14, the estimates were not significant. For group II genitors, strains LM-588-11-1 and LM-588-11-4 showed positive CGC for NTR and MTR respectively (**Table 2**). Jagosz[13] found that for carrot root productivity, strains with high CGC produce the hybrids with the highest CEC.

For leaf-burn tolerance (QDF), considering the crosses that stood out for root yield and were stable in both years, higher negative values were obtained for the crosses LM-649 × LM-555-2-1, LM-650 × LM-555-7-1 and LM-650 × LM-554-8-1. From the first cross, strain LM-649 stood out in relation to CGC for MRC, MTR and QDF, while strain LM-555-2-1 did not show good performance for these characters, in relation to CGC, but by gene complementarity, with non-additive action, the hybrid obtained stood out positively. The LM-650 strain of the two other crosses contributed with additive genes for NRC and MTR; the LM-554-8-1 strain contributed with additive action genes for MRC and MTR, while the LM-555-7-1 strain also showed good gene complementarity and contributed with non-additive genes. The highest levels of tolerance to QDF were obtained by the last two hybrids, which were formed by genitors that did not have negative CGC values for this character, suggesting that for QDF, the CEC was more important, agreeing with the observations of Carvalho *et al.*[14] that verified a predominance of non-additive effects for tolerance to leaf-burn, also with the evaluation of hybrids of tropical and temperate genotypes.

4. Conclusions

The genitors with the highest overall combining ability for root yield were the male-fertile strains LM-649 and LM-650 and the male-fertile strain 555-2-2.

The best hybrids for root yield and leaf blight resistance were LM-649 × LM-555-11-1, LM-650 × LM-555-7-1 and LM-650 × LM-554-8-1.

Conflict of interest

The authors declare no conflict of interest.

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