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Evaluation of tropicalized carrot lines using partial diallel

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Abstract: Carrot is one of the main vegetables grown in Brazil, and the seed market for this crop requires the continuous development of news cultivars with high agronomic potential. In this context, hybrid carrot cultivars stand out, as they have high-quality roots and excellent yield potential. The objective of this study was to evaluate the effects of general (GCA) and specific (SCA) combining ability between different summer carrot lines for production components, tolerance to leaf blight, and to identify the most promising lines. Crosses were performed in a partial diallel scheme 7x3, using seven male-sterile lines of Asian origin and three male-fertile parents of tropical origin, from the breeding program at Embrapa Vegetables. The experiment was conducted at the experimental field of Embrapa Vegetables, Brasília-DF, Brazil, during the 2020/21, 2021/22, and 2022/23 harvest. The experimental plot consisted of a seedbed with 1.2 m^2, in RCBD ant three replications. The 21 hybrids were evaluated for tolerance to leaf blight (LB) at 90 days after sowing, and for total (TY), commercial (MY), and uncommercial (UY) root mass, and the number of marketable roots (NMR) and unmarketable roots (NUR) at 100 days after sowing. Analysis of variance and estimates of the effects of GCA and SCA were performed. GCA effects predominated over SCA for most production component traits, although SCA effects were also important, especially for controlling the expression of the LB trait. There were significant differences for the interaction between crosses x harvest of evaluation and GCA and SCA components x harvests. It was possible to select the lines A5, A7 (male-sterile), and C1 (male-fertile) as the most promising parents for the composition of summer carrot hybrids.

Key-words: *Daucus carota* L.; hybrids, selection; combination.

Avaliação de linhagens de cenoura tropicalizadas utilizando dialelo parcial

Resumo: A cenoura é uma das principais hortaliças cultivadas no Brasil, e o mercado de sementes dessa cultura exige um desenvolvimento contínuo de cultivares melhoradas com alto potencial agronômico. Nesse contexto, destacam-se as cultivares híbridas de cenoura, que apresentam raízes de alta qualidade e excelente potencial produtivo. O objetivo deste estudo foi avaliar os efeitos da capacidade geral (CGC) e específica (CEC) de combinação entre diferentes linhagens de cenoura de verão para componentes de produção e tolerância à queima das folhas, visando identificar as linhagens mais promissoras para serem usadas em cruzamentos. Os cruzamentos foram realizados em esquema dialelo parcial 7x3, utilizando sete linhagens macho-estéreis de origem asiática e três genitores macho-férteis de origem tropical, do programa de melhoramento da Embrapa Hortaliças. O experimento foi conduzido no campo experimental da Embrapa Hortaliças, Brasília-DF, Brasil, durante as safras 2020/21, 2021/22 e 2022/23. A parcela experimental consistiu em um canteiro com 1,2 m^2, em DBC e três repetições. Os 21 híbridos foram avaliados quanto à tolerância à queima das folhas aos 90 dias após a semeadura, e quanto à massa total, comercial e não comercial de raízes e; número de raízes comercializáveis e não comercializáveis aos 100 dias após a semeadura. Foi realizada análise de variância e estimativas dos efeitos da CGC e CEC. Predominaram os efeitos da CGC sobre a CEC para a maioria dos caracteres componentes de produção, embora os efeitos de CEC também tenham sido importantes, principalmente para o controle da manifestação do caráter queima das folhas. Houve diferenças significativas para a interação entre cruzamentos x safras e dos componentes GCA e SCA x safras. Foi possível selecionar as linhagens A5 e A7 (macho-estéreis) e C1 (macho-fértil) como os genitores mais promissores para a composição de híbridos de cenoura de verão.

Palavras-chave: *Daucus carota* L.; híbridos, seleção; combinação.

1. INTRODUCTION

Carrots are an important vegetable crop cultivated in Brazil. According to the IBGE, in 2017, more than 25,000 producers cultivated this crop, generating a production of over 480,000 tons of marketable roots (IBGE, 2017).

In Brazil, the expansion of carrot cultivation to tropical regions and the summer season throughout the country occurred, among other factors, due to the development of the Brasília cultivar, released by Embrapa Vegetables and ESALQ/USP in the early 1980s. Being adapted to heat, it allowed planting during hotter and rainier seasons (VIEIRA et al., 1983).

To synthesize hybrid cultivars, the breeders need to develop and evaluate a large number of lines. Most of the time, it is not possible to evaluate all possible hybrid combinations, being necessary to use quantitative genetics methods, such as the studies of general combining ability (GCA) and specific combining ability (SCA), suggested by Sprague & Tatum (1942). These methods help in selecting the most promising genitors for hybrid synthesis by evaluating the lines based on their average performance (GCA) or specific performance in a hybrid combination (SCA).

Some methodologies for estimating the parameters of general and specific combining abilities in line crosses were proposed by Griffing (1956), Gardner & Eberhart (1966), and Hayman (1954). However, these methods involve a large number of crosses and do not always provide all the necessary information. Therefore, partial or circulant diallel schemes have been proposed to reduce the number of crosses to be performed and provide information about a relatively large set of lines (CRUZ et al., 2012). In the case of partial diallel, the crosses involve parental plants allocated into two groups, and the inferences are obtained separately for each group.

In Brazil, few companies carry out carrot breeding with the aim of developing hybrid cultivars. Among these, only public companies conduct research and provide results on the evaluation of combining ability between lines or the performance of hybrid combinations. Carvalho et al. (2014) evaluated a set of carrot hybrids obtained through crosses in a 2 x 5 partial diallel scheme, two tropical lines crossed with five carrot lines of temperate origin, for reaction to leaf blight disease and carrot yield components. They found predominant GCA effects over SCA effects for root yield traits and more pronounced SCA effects for leaf blight severity. In another study by Carvalho et al. (2021), the additive effects of genes or GCA were predominant for both yield and leaf blight severity, indicating the importance of determining both SCA and GCA effects.

In another study, Simon & Stradberg (1998) evaluated five divergent lines widely used in US carrot breeding programs for tolerance to alternaria and found predominant additive effects in the control of this trait, with some dominance effect. Regarding yield, Duan et al. (1996) and later Guan et al. (2001) found heterosis effects and predominance of GCA effects in studies with carrot hybrids, although the non-additive effects of alleles (SCA) also significantly contributed to yield in most hybrid combinations.

Therefore, this study aimed to estimate the CGC and CEC between two groups of carrot lines for yield components and tolerance to leaf blight and to identify tester lines for future hybrid combinations.

2. MATERIAL AND METHODS

Twenty-one experimental carrot hybrids were evaluated, originating from controlled crosses between two groups of genitors, using a partial diallel scheme (7×3), as described in "experiment 2" by Comstock & Robinson (1948). This model involves the evaluation of progenitors arranged in two groups, which may or may not belong to a common set (CRUZ et al., 2012).

Group I parental plants consisted of male sterile lines, coded as A1, A2, A3, A4, A5, A6 and A7. Group II consisted of male-fertile genitors: C1, C2, and C3. The first group of lines was obtained by self-pollination of carrots from the Kuroda group, while the second group is descended from the Brasília group (Table 1).

Table 1. Lines and codes used in the synthesis of experimental hybrids

Group I - Sterile		**Group II - Fertile**	
Lines	Code	Lines	Code
LM-705-21-2	A1	LM-555-60-1	C1
LM-705-7-1	A2	LM-588-11-4	C2
LM-705-50-1-2	A3	LM-555-7-1	C3
LM-705-31-1-1	A4		
LM-705-12-2	A5		
LM-705-28-1-2	A6		
LM-705-55-3-1	A7		

The experiments were conducted in Brasília-DF during the harvests 2020/21, 2021/22, and 2022/23. The average monthly temperatures (°C) and the total monthly precipitation (mm) for the periods during which the experiments were conducted are presented in Figure 1.

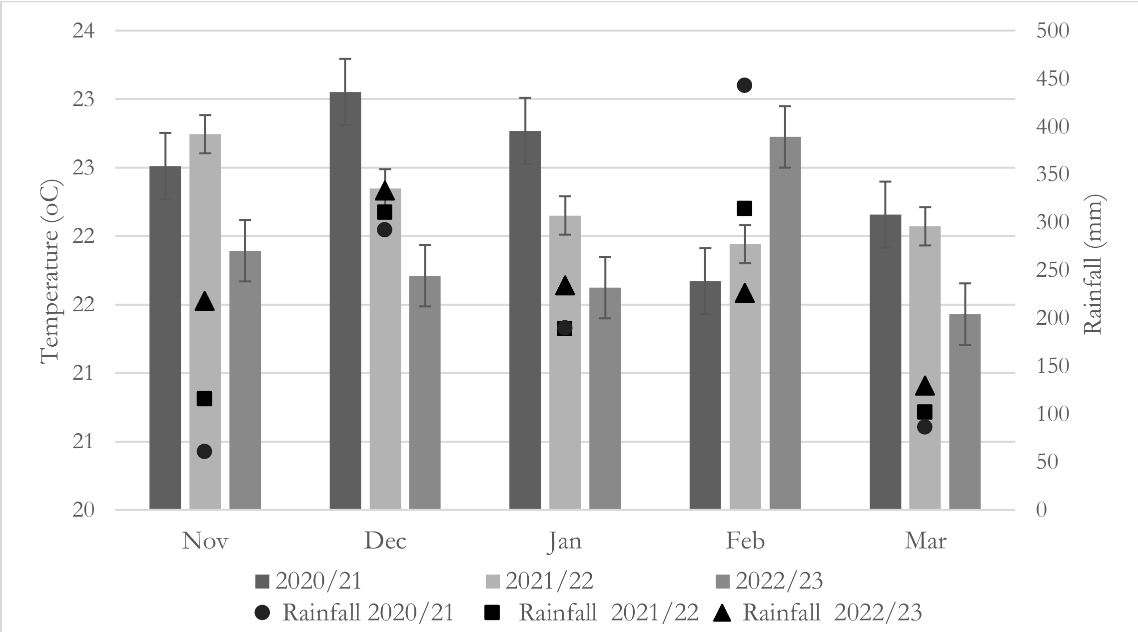

Figure 1. Monthly mean temperature (°C) and total monthly precipitation (mm) during the evaluation periods of carrot experiments in the 2020/21, 2021/22, and 2022/23 harvest in Brasília-DF. Source: INMET (2024).

The soil tillage was carried out with plowing and harrowing. Then, 1.0-meter-wide beds were formed and manually fertilized by broadcasting with the equivalent of 2,000 kg ha^{-1} of the commercial formulated fertilizer (N-P-K) 04-14-08 plus boron and zinc. The fertilizer was incorporated into the beds using a bed former machine.

The experiments were carried out in a randomized block design with three replications, with plots of 1.2 m^2 (1 m width and 1.2 m length). The sowing was carried out in the second half of November or the first week of December, in furrows arranged transversely on the beds, with a double spacing of 10 cm between single rows and 20 cm between double rows, totaling four double rows per plot.

Weed control was carried out using the herbicide linuron, at a rate equivalent to 2.2 liters of active ingredient per hectare, four days after sowing. Thinning of the plants was done 30 days after sowing, maintaining an approximate spacing of 5 cm between plants. Subsequently, topdressing was applied manually with 400 kg per hectare of ammonium sulfate (N = 21%). The irrigation, when necessary, was applied using conventional sprinkler systems until the soil reached field capacity. No fungicides or bactericides were used for disease control. Other cultural practices inherent to cultivation were carried out as described by Filgueira (2003).

At 98 days after sowing, the severity of leaf blight (caused by *Alternaria dauci*, *Cercospora carotae*, and *Xanthomonas hortorum* pv. carotae) was assessed in the plots. At 100 days, the plots were harvested, and the following traits were evaluated: marketable yield (MY, t ha^{-1}), unmarketable yield (UY, t ha^{-1}), total yield (TY, t ha^{-1}), number of marketable roots (NMR, x 1000 ha^{-1}), number of unmarketable roots (NUR, x 1000 ha^{-1}), and leaf blight severity (LB, in percentage). Roots were considered marketable if they had a minimum diameter of 2.5 cm and length of 14 cm, free of external defects, smooth and cylindrical.

Data were evaluated for normality of distribution (Lilliefors test) and homogeneity of variance (Bartlett's test) (Steel & Torrie, 1980) of residuals. Subsequently, analysis of variance and partial diallel analysis were performed using the statistical software GENES (CRUZ, 2016).

3. RESULTS AND DISCUSSION

The effects corresponding to the mean squares of the crosses, general combining ability of group 1 (GCA-I) and group 2 (GCA-II), and the specific combining ability (SCA I x II) for the traits marketable yield (MY, t ha^{-1}), unmarketable yield (UY, t ha^{-1}), total yield (TY, t ha^{-1}), number of marketable roots (NMR, x 1000 ha^{-1}), number of unmarketable roots (NUR, x 1000 ha^{-1}), and leaf blight severity (LB, in percentage) for the three evaluation years are presented in Table 2.

The experimental coefficients of variation (CV%) ranged from 1.15% for TY in the 2022/23 harvest to 39.36% for LB in the 2020/21 harvest. These values are within the variation coefficients for carrot experiments evaluating diallel schemes. Coelho et al. (2024), evaluating summer carrot hybrids under field conditions over two agricultural years, obtained values ranging from 5.85% for root diameter to 58.30% for leaf blight severity, demonstrating consistency with the findings in the present study.

Among the crosses, highly significant differences ($p \leq 0.01$) were found for all evaluated traits by the F test, except for MY in the 2020/21 harvest and LB in the 2022/23 harvest. This demonstrates that there are significant variations in the performance of the evaluated hybrids, and that the groups of lines used express different behaviors in the hybrid's combinations.

The effects of General Combining Ability (GCA) are estimated based on the average performance of a line when crossed with a set of other genotypes, and are related to the additive effects of alleles or additive epistatic interactions. On the other hand, Specific Combining Ability (SCA) refers to a specific interaction between two parental plants in a cross, and its average can be higher or lower than the average of the progenitors; it is related to dominance effects and epistasis (Cruz & Vencovsky, 1989; Griffing, 1956).

For GCA-I, the trait MY showed highly significant differences ($p \leq 0.01$) for the 2021/22 harvest and significant differences for the 2022/23 harvest ($p \leq 0.05$), indicating that this group of lines may exhibit different behaviors depending on the evaluated harvest. For UY, there were highly significant differences ($p \leq 0.01$) observed only in the 2022/23 harvest. Significant ($p \leq 0.05$) or highly significant ($p \leq 0.01$) differences were found for the traits TY, NMR, and NUR, except for NMR in the 2021/22 harvest. LB showed differences among group I lines only in the 2021/22 harvest.

For GCA-II, highly significant differences ($p \leq 0.01$) were observed for UY and NUR in the 2020/21 harvest; for MY, UY, TY, and LB in the 2021/22 harvest; and for all traits, except LB, in the 2022/23 harvest.

The significance of GCA-I effects suggests the possibility of identifying more promising lines in the combination of summer or mid-season hybrids. Although originating from Asian germplasm, these lines demonstrate sufficient variability to produce hybrids that are more productive and/or more tolerant to leaf blight. Carrot populations, due to their high genetic variability, generate divergent lines through the process of self-pollination, even in populations with advanced degrees of genetic breeding. Regarding leaf blight, Simon & Strandberg (1998) studied genetic variability among temperate lines and found significant differences, concluding that these lines can contribute differently in hybrids for greater or lesser tolerance to this disease.

The specific combining ability (SCA) was significant ($p \leq 0.05$) or highly significant ($p \leq 0.01$) for most evaluated traits, except for LB in the 2022/23 harvest. Predominant effects of GCA over SCA are commonly observed in the literature (DUAN et al., 1996; GUAN et al., 2001; JAGOSZ, 2012; CARVALHO et al., 2014; CARVALHO et al., 2016; COELHO et al., 2024). Typically, additive effects of alleles have a greater influence on yield related traits than other characteristics in carrots, such as resistance to leaf blight. In the present study, the synthesis of hybrids from different genetic groups, i.e., divergent groups, influenced dominant effects, but these did not exceed the additive effects of alleles, as observed in the GCA ratio for most evaluated traits.

For MY (Figure 2A), there were small GCA effects for the agricultural year 2020/21. However, for the other agricultural years, there were pronounced effects, with lines A5 and A7 from group I standing out. Lines A1 and A2 from group I mainly presented negative effects. For Group II, line C1 stood out with positive effects in all years, while line C2 had small positive or negative effects depending of the agricultural year. Line C3 showed a small positive effect in the 2020/21 season and negative effects in the other agricultural years, having the worst performance in group II.

Line A5 from Group I and Line C1 from Group II contributed to the increase in NMR. For UY, the line from Group I that contributed to the reduction of this trait was A7, while for Group II, C1 consistently contributed to the reduction of this trait value. For NUR, the same lines contributed to the reduction of this trait, with the addition of Line A3 from Group I.

For UY, the line from Group I that contributed to the reduction of this trait value was A7, while from Group II, C1 consistently contributed to the reduction of this trait value. For NUR, the same lines contributed to the reduction of value, with the addition of line A3 from Group I, which also reduced NUR values.

Breeding programs aiming at hybrid cultivars in many crops require a large number of hybrid combinations to increase the chances of finding a superior combination that can be released as a new cultivar (RESENDE & ALVES, 2021). Generally, diallel schemes are not used due to their complexity (CARVALHO et al., 2014). In practice, topcross schemes are more commonly used in breeding programs with this objective (NURMBERG et al., 2000). In this method, the performance of a set of unknown lines is evaluated by crossing them with a standard tester, which can be a line with known and stable genetic behavior (BORÉM et al., 2021).

Although the diallel scheme is labor-intensive, it can be a useful indicator for selecting genotypes to be used as testers in topcrosses. In the present study, the male-sterile lines A5 and A7 were identified as the most promising to be used as testers, while in group II, line C1 stood out as a candidate tester.

In carrot breeding programs, the development of male-sterile (A line), maintainer (B line), and fertile (C line) lines is quite laborious. Therefore, schemes that allow the identification of superior male-sterile lines are essential to concentrate efforts on the C lines, aiming to evaluate a large number of lines and consequently hybrid combinations.

The effects of specific combining abilities of the 21 hybrids evaluated in Brasília-DF over three agricultural years are presented in Figure 3.

Table 2. Mean squares diallel analysis for marketable yield (MY, t ha^{-1}), unmarketable yield (UY, t ha^{-1}), total yield (TY, t ha^{-1}), number of marketable roots (NMR, x 1000 ha^{-1}), number of unmarketable roots (NUR, x 1000 ha^{-1}) and severity of leaf blight (LB in percentage), Brasília, Embrapa Vegetables, 2024.

		Mean Square					
FV	GL	MY	NMR	UY	NUR	TY	LB
2020/21 harvest							
Crossing (C)	20	24.88^{ns}	3347.09**	24.12**	30709.64**	37.69**	404.86**
GCA I	6	15.36 ^{ns}	2284.54 ^{ns}	20.11**	37338.36**	31.99*	259.65^{ns}
GCA II	2	10.75 ^{ns}	742.86 ^{ns}	30.45**	32262.24**	5.05^{ns}	392.56^{ns}
SCA	12	31.99*	4312.41**	25.07**	27136.52**	45.98**	479.52**
Residue	41	14.48	1365.59	4.39	1366.59	12.19	163.49
Mean		15.10	151.43	9.81	240	24.91	32.33
GCA: SCA		0.82	0.70	2.02	2.56	0.81	1.36
CV%		25.20	24.22	21.09	15.04	13.95	39.36
2021/22 harvest							
Crossing (C)	20	231.90**	4960.61**	41.34**	4859.24**	225.86**	200.43**
GCA I	6	376.37**	1126.65^{ns}	62.86**	781.57^{ns}	402.91**	276.38**
GCA II	2	201.72**	1893.16^{ns}	19.49*	643.35^{ns}	111.31**	176.15**
SCA	12	164.69**	7388.83**	34.22**	7600.73**	156.42**	166.51**
Residue	20	18.06	843.86	3.83	843.86	5.25	0.01
GCA: SCA		3.51	0.41	2.41	0.19	3.29	2.72
Mean		36	334.53	17.6	346.34	53.6	23.92
CV%		12.02	8.81	11.30	8.21	4.35	0.30
2022/23 harvest							
Crossing (C)	20	250.13**	7930.20**	23.20**	8059.30**	298.65**	159.03^{ns}
GCA I	6	178.06*	4927.97**	18.09**	6962.68**	212.95*	95.45^{ns}
GCA II	2	434.81**	20384.60**	35.01**	10859.55**	271.06*	252.46^{ns}
SCA	12	255.38**	7355.58**	23.79**	8140.90**	346.09**	175.25^{ns}
Residue	20	70.06	41.32	0.01	41.32	71.98	85
GCA: SCA		2.40	3.44	2.23	2.19	1.40	1.99
Mean		29.74	234.88	9.63	238.06	39.82	28.13
CV%		25.39	2.61	1.15	2.64	19.31	20.25
joint analysis							
Harvest(H)	2	7252.53**	529411.54**	1303.11**	241869.30**	12972.91**	1114.16**
C x H	40	132.22**	5261.48**	24.25**	12427.71**	165.85**	143.61^{ns}
GCA I x H	12	144.93**	3066.20**	32.60**	11560.82**	208.77**	172.56 ^{ns}
GCA II x H	4	113.33**	4633.48**	19.44**	14042.64**	81.89*	31.90 ^{ns}
SCA x H	24	129.01**	6463.78**	20.87**	12592.00**	158.38**	147.76 ^{ns}
Residue	81	29.09	909.79	3.17	910.29	25.24	103.74
GCA: SCA		2,00	1,19	2,49	2,03	1,84	1,38
Mean		26,95	240,28	12,34	274,80	39,44	28,13
CV%		18.67	17.75	24.05	16.14	12.68	40.41

Significant difference for test of F.: *-significant at 5% of probability, **-significant at 1% probability, and ^{ns}, not significant.

The effects of the general combining ability (GCA) of groups I and II of lines evaluated in the agricultural years 2020/21, 2021/22, and 2022/23 are presented in Figure 2.

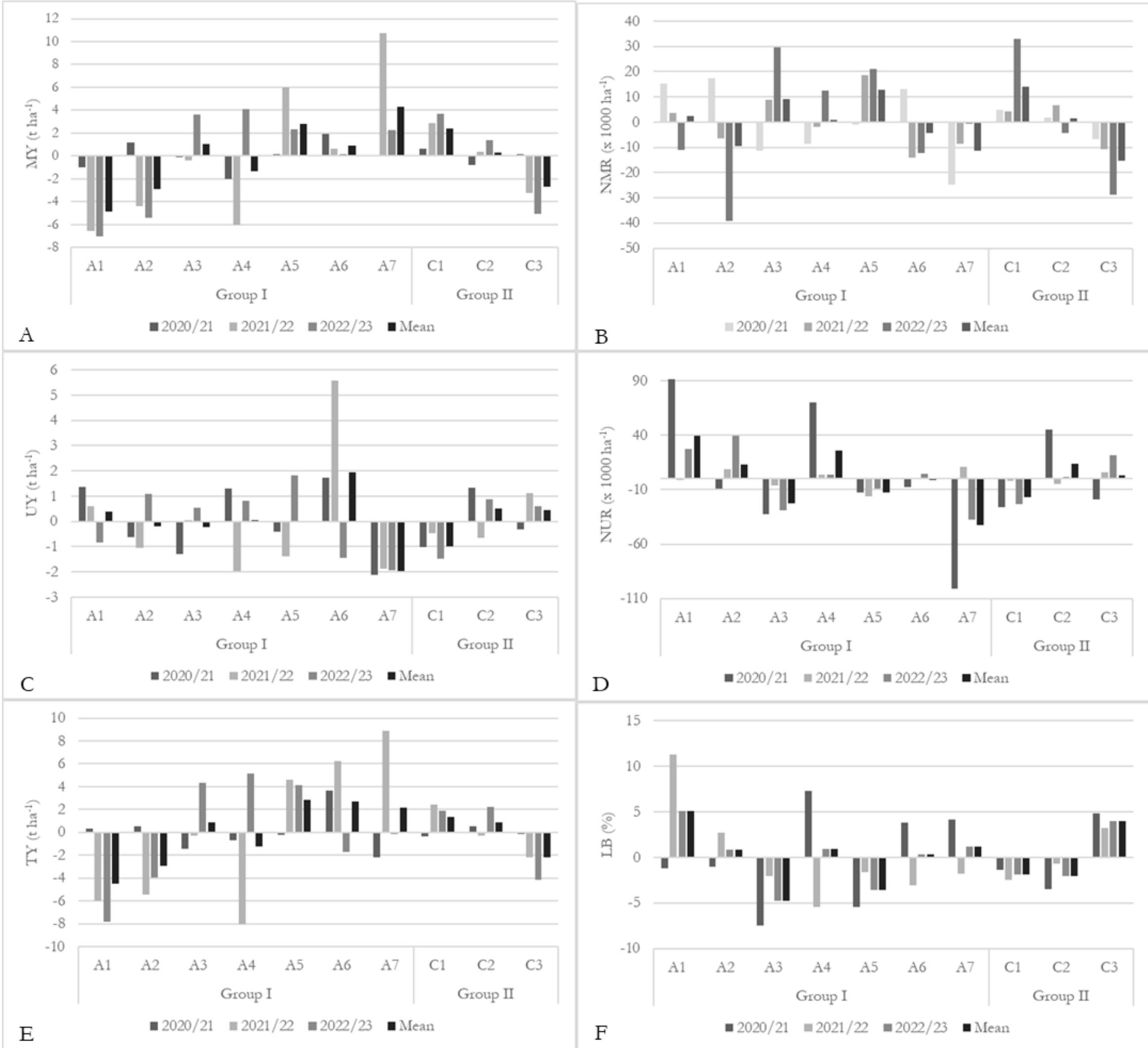

Figure 2. Effects of general combining ability (GCA) to marketable yield (MY, t ha^{-1}), unmarketable yield (UY, t ha^{-1}), total yield (TY, t ha^{-1}), number of marketable roots (NMR, x 1000 ha^{-1}), number of unmarketable roots (NUR, x 1000 ha^{-1}) and severity of leaf blight (LB in percentage), Brasília, Embrapa Vegetables, 2024.

For MY (Figure 3A), most hybrid combinations showed variable behaviors throughout the different harvests. The combinations that consistently showed results below the overall average were A3xC2, A4xC3 and A7xC2. Regarding the NMR (Figure 3B), the hybrid combinations that consistently showed positive results throughout the harvests were A3xC3, A4xC2, A5xC3 and A7xC1. On the other hand, the combinations that consistently showed negative results were A5xC1, A5xC2, A6xC1 and A7xC2.

For UY (Figure 3C), the combinations that resulted in greater mass of non-commercial quality roots were A3xC3, A4xC1, A5xC1, A5xC3, A6xC1 and A7xC3. In the case of NUR (Figure 3D), the combinations that presented the highest values throughout the three years of evaluation were A2xC2, A5xC1, A6xC1, A6xC2 and A7xC3.

For TY (Figure 3E), the combinations that demonstrated positive values throughout all harvests were A4xC2, A5xC3, A7xC1 and A7xC3. The LB trait (Figure 3F) remained stable throughout the different agricultural years. The hybrid combinations that presented negative values, reducing the severity of leaf blight, were A1xC1, A2xC1, A3xC3, A4xC1, A5xC2 and A6xC3.

Diallel evaluation not only helps in finding good parents with high general combining ability (GCA) but also identifies hybrid combinations that, due to dominance effects, show high performance and can be candidates for release as cultivars (LIMA et al., 2023). For example, the combination A4 x C2 stands out for being stable in all harvests, even though its parents did not overhang in terms of GCA. Ideally, it would be best to combine parents with high GCA and specific combining ability (SCA). This was possible, for instance, with the combination A7 x C1, which showed a mean over the three years of evaluation of 36.78 t ha^{-1} (data not shown). This value includes the overall mean of the experiments over the three years of 26.95 t ha^{-1} (Table 2), plus the contributions of the GCAs of lines A7 and C1, which were 4.31 t ha^{-1} and 2.41 t ha^{-1}, respectively (Figure 2A), in addition to the SCA effect of the cross A7 x C1, which was 3.11 t ha^{-1} (Figure 3A).

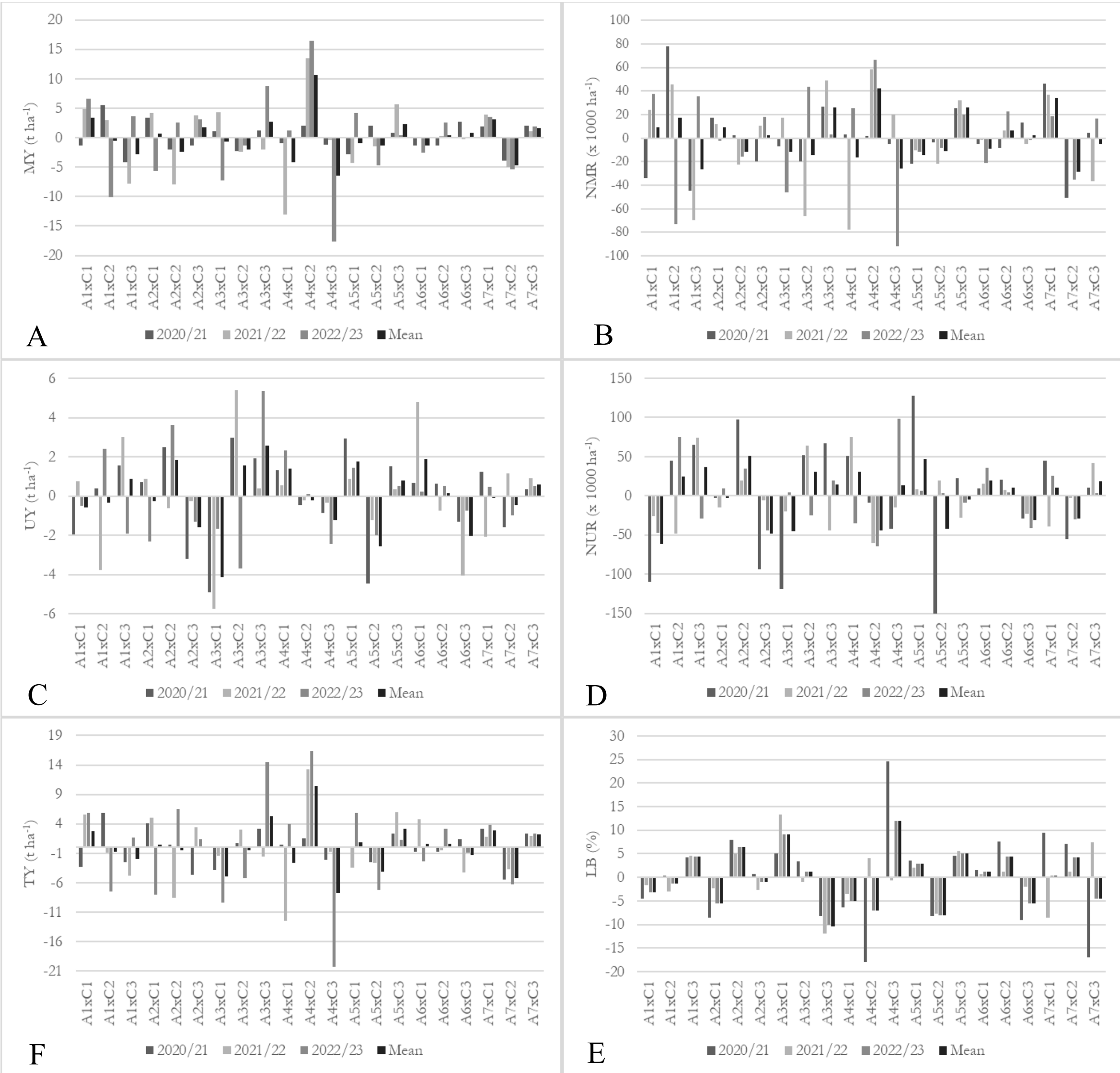

Figure 3. Effects of specific combining ability (SCA) to marketable yield (MY, t ha^{-1}), unmarketable yield (UY, t ha^{-1}), total yield (TY, t ha^{-1}), number of marketable roots (NMR, x 1000 ha^{-1}), number of unmarketable roots (NUR, x 1000 ha^{-1}) and severity of leaf blight (LB in percentage), Brasília, Embrapa Vegetables, 2024.

4. CONCLUSIONS

There were predominant effects of GCA for most of the evaluated traits; however, the effects of SCA are also important in the expression of traits less influenced by the harvest.

Lines A5 and A7 from Group I and line C1 from Group II were selected to be used as parents for future hybrids.

5. ACKNOWLEDGMENT

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