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Selection of parents and segregating populations of carioca common bean resistant to *Fusarium* wilt

Seleção de genitores e populações segregantes de feijão carioca resistentes à murcha de fusário

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Highlights

Selection of resistant genotypes in a field infested with *Fusarium* wilt.
Additive and non-additive effects control the reaction to *Fusarium* wilt.
BRS Notável contributes positively to all evaluated traits.
Four populations are promising for obtaining superior lines.

Abstract

Fusarium wilt (*Fusarium oxysporum* f. sp. *phaseoli*) is one of the most common diseases in the common bean (*Phaseolus vulgaris*) crop, and the most viable alternative for its control is the use of resistant cultivars. However, the number of "carioca" cultivars, the most important commercial group in Brazil, which has a good level of resistance to this disease, is still low. To obtain populations with a higher degree of resistance, seven parents with different levels of resistance to *Fusarium* and which produce carioca grains were crossed in a complete diallel design. The 21 segregating populations obtained were evaluated in the years/generations 2012/F_3, 2013/F_4, and 2014/F_5 in experiments in Santo Antônio de Goiás, GO, in the winter crop season (sowing in May), together with the check cultivars BRS Notável (resistant) and BRS Cometa (susceptible) in an area naturally infested with *Fusarium oxysporum* f. sp. *phaseoli*, under a center pivot irrigation system. Reaction to *Fusarium* wilt, yield, and 100-seed weight were evaluated. Additive and non-additive effects contributed to control of reaction to Fusarium wilt, yield, and 100-seed weight. The statistically negative general combining ability ($\hat{g}_i$) estimates for BRS Notável (-0.51), CNFC 15872 (-0.20), IPR Juriti (-0.18), and BRSMG Talismã (-0.13) indicate that these parents are recommended for obtaining populations more resistant to Fusarium wilt. Among them, cultivar BRS Notável also showed a statistically positive $\hat{g}_i$ estimate for grain yield (87.90). Among the parents recommended for resistance to Fusarium wilt, cultivars IPR Juriti (0.99) and BRS Notável (0.23) are those that most contributed to obtaining populations with larger-sized beans. Cultivar BRS Notável is the most promising parent for participation in new crossing

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blocks, showing non-zero $\hat{g}_i$ estimates for all traits, favoring an increase in resistance to *Fusarium* wilt, yield, and 100-seed weight. Populations BRS Notável / CNFC 15872, BRS Ametista / BRS Notável, BRS Notável / BRSMG Talismã, and BRS Ametista / BRSMG Talismã showed good mean values for reaction to *Fusarium* wilt, yield, and 100-seed weight and at least one parent with a good general combining ability estimate for resistance to *Fusarium* wilt. These four populations are promising for obtaining lines with superior performance for resistance to *Fusarium* wilt, yield, and larger-sized grains.
Key words: Complete diallel. *Fusarium oxysporum* f. sp. *phaseoli.* 100-seed weight. *Phaseolus vulgaris.* Yield.

Resumo

A murcha de fusário (*Fusarium oxysporum* f. sp. *phaseoli*) é uma das doenças mais importantes para a cultura do feijão (*Phaseolus vulgaris*) e a alternativa mais viável para o seu controle é a utilização de cultivares resistentes. No entanto, o número de cultivares do grupo comercial carioca, que é o mais importante no Brasil, com bom nível de resistência à essa doença ainda é pequeno. Para a obtenção de populações com maior grau de resistência, sete genitores com diferentes níveis de resistência à murcha de fusário e grãos do tipo carioca foram intercruzados em esquema de dialelo completo. As 21 populações segregantes obtidas foram avaliadas nos anos/gerações 2012/F_3, 2013/F_4 e 2014/F_5, em experimentos em Santo Antônio de Goiás, GO, na época do inverno (semeadura em maio), juntamente com as testemunhas BRS Notável (resistente) e BRS Cometa (suscetível), em área naturalmente infestada com *Fusarium oxysporum* f. sp. *phaseoli*, sob irrigação com pivô central. Foram avaliadas a reação à murcha de fusário, produtividade e massa de 100 grãos. Os efeitos aditivos e não aditivos contribuíram no controle da reação à murcha de fusário, produtividade e massa de 100 grãos. As estimativas da capacidade geral de combinação ($\hat{g}_i$) negativas e diferentes de zero para BRS Notável (-0,51), CNFC 15872 (-0,20), IPR Juriti (-0,18) e BRSMG Talismã (-0,13), indicaram que estes genitores são recomendados para a obtenção de populações mais resistentes à murcha de fusário e entre eles, a cultivar BRS Notável mostrou também estimativa de $\hat{g}_i$ positiva e diferente de zero para produtividade de grãos (87,90). Entre os genitores recomendados para resistência à murcha de fusário, as cultivares IPR Juriti (0,99) e BRS Notável (0,23) são as que mais contribuíram na obtenção de populações com maior tamanho de grãos. A cultivar BRS Notável é o genitor mais promissor para participar de novos blocos de cruzamentos, apresentando estimativas de $\hat{g}_i$ diferentes de zero para todos os caracteres, favorecendo o incremento da resistência à murcha de fusário, produtividade e massa de 100 grãos. As populações BRS Notável / CNFC 15872, BRS Ametista / BRS Notável, BRS Notável / BRSMG Talismã e BRS Ametista / BRSMG Talismã apresentaram boas médias para reação à murcha de fusário, produtividade e massa de 100 grãos, e pelo menos um genitor com boa estimativa da capacidade geral de combinação para resistência à murcha de fusário. Estas quatro populações são promissoras para a obtenção de linhagens superiores para resistência à murcha de fusário, produtividade e maior tamanho de grãos.
Palavras-chave: Dialelo completo. *Fusarium oxysporum* f. sp. *phaseoli.* Massa de 100 grãos. *Phaseolus vulgaris.* Produtividade.

Introduction

Common bean, or dry bean (*Phaseolus vulgaris* L.), is the main legume consumed in direct form in Brazil and is a primary source of protein in the human diet (Semba et al., 2021). Brazilian production of common bean is around 2.3 million metric tons annually (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2022), distributed across three different crop seasons (rainy, dry, and winter). Different types of common bean grains are consumed in Brazil, but the carioca commercial type (cream-colored seed coat with brown streaks) represents around 70% of Brazilian production (Souza et al., 2013). However, diseases are one of the factors that affect the yield potential of the crop.

Fusarium wilt, caused by the soil fungus *Fusarium oxysporum* f. sp. *phaseoli,* has caused considerable economic losses in the common bean crop, compromising yield up to 80% (M. J. Z. Pereira et al., 2008; Torres et al., 2021). This disease occurs throughout Brazil, but highly impacts the Central region in the winter crop season (sowing from April to June), where successive common bean crops are grown under center pivot irrigation systems in humid and mild temperature conditions, which are favorable to the development of the pathogen (Batista et al., 2017; Xue et al., 2015). The use of cultivars with genetic resistance is the recommended practice for its effective control (Carneiro et al., 2015).

One of the important factors for obtaining more resistant common bean cultivars is the existence of genetic variability for reaction to this disease, which has been shown in various studies (Batista et al., 2016; D. G. Pereira et al., 2019a, 2020; H. S. Pereira et al., 2016, 2019b; M. J. Z. Pereira et al., 2011; Torres et al., 2021). Nevertheless, even now, most of the carioca grain type cultivars available are susceptible, especially those with more upright plant architecture and lighter-colored seed coats. Genetic control of reaction to *Fusarium* wilt has not yet been clearly described (Negreiros et al., 2020). According to some reports, resistance is monogenic (R. de L. D. Ribeiro & Hagedorn, 1979) and controlled by more than one gene (Batista et al., 2017; Cândida et al., 2009), and polygenic control has also been suggested (Fall et al., 2001).

One of the procedures employed to select promising parents and segregating populations and to study the genetic effect of the traits is diallel crossing (C. D. Cruz et al., 2012). This type of design has been used for various traits in the common bean crop, e.g. grain yield (D. G. Pereira et al., 2019a), early maturity (Vale et al., 2015), reaction to white mold (Ferreira et al., 2018), reaction to common bacterial blight (Trindade et al., 2015), drought tolerance (Gonçalves et al., 2015), and iron and zinc concentration in the grain (Di Prado et al., 2019). Some studies have also been performed for reaction to *Fusarium* wilt (Batista et al., 2016; D. G. Pereira et al., 2019a; Torres et al., 2021) and showed that the dominance and additive effects were important.

Most studies evaluating lines and/or segregating populations for this disease have been conducted under controlled conditions, involving inoculation of the pathogen (Batista et al., 2016; Cândida et al., 2009; M. J. Z. Pereira et al., 2008, 2011; Paulino et al., 2020). However, field studies are indispensable for the confirmation of resistance (D. G. Pereira et al., 2019a; H. S. Pereira et al., 2016; Torres et al., 2021, 2022). For the inoculation of the fungus *F. oxysporum* f. sp. *phaseoli*, it is important that the prevalent races be properly defined. At least seven races have been described in the literature (Alves-Santos et al., 2002; Henrique et al., 2015; Woo et al., 1996). Nonetheless, there is variation in the systems that assist in defining the races. The series of differentiating cultivars are composed of different cultivars, and since they do not clearly express the phenotype of resistance or susceptibility, they are insufficient for classification of the isolates (Alves-Santos et al., 2002; A. F. Cruz et al., 2018; Henrique et al., 2015; Negreiros et al., 2020; Paulino et al., 2020).

Thus, the aim of this study was to investigate the genetic control of reaction to *Fusarium* wilt and identify parents and segregating populations of common bean of the carioca commercial grain type that are resistant to *Fusarium* wilt and have greater yield and 100-seed weight, through evaluations in pathogen-infested fields.

Materials and Methods

Crosses were performed in a complete diallel design without reciprocal crosses between seven common bean lines with carioca grain type that exhibit some level of resistance to *Fusarium* wilt. The previously identified lines used were BRS Ametista (PR9115957 / LR720982CP), BRS Notável (A769 /4/ A774 /// A429 / XAN252 // V8025 / G4449 /// WAF2 / A55 // GN31 / XAN170), BRS Requinte (Carioca MG // POT94 / AN910523), BRSMG Talismã (BAT477 / IAPAR14 / FT84-29 / Jalo EEP558 / A252 / A77 / Ojo de Liebre / ESAL645 / Pintado / Carioca / P85 / P103 / H4 / AN910522 / ESAL624 / Carioca MG), CNFC 15872 (São José / Goytacazes), IPR Juriti (Carioca 99 selections / Great Northern Nebraska 1 Selection # 27 // BAT93 // Aroana selections // A176 / A259 // II – 133 / XAN87), and Pérola (selection on cultivar Aporé) (D. G. Pereira et al., 2020; H. S. Pereira et al., 2012, 2016, 2018). Crosses were carried out in a greenhouse in Santo Antônio de Goiás, GO, Brazil, in 2010. The F1 seeds were also sown in a greenhouse to obtain F_2 seeds, which, in turn, were sown in the field in the 2011 winter crop season (sowing in May) for multiplication.

The 21 segregating populations were evaluated in 2012, 2013, and 2014 in the F_3, F_4, and F_5 generations, respectively, using two check cultivars: BRS Notável (resistant) and BRS Cometa (susceptible) (H. S. Pereira et al., 2016, 2018). Thus, the effect of the years was mixed with the effect of the generations. The experiments were conducted in a randomized block design with three replications, in the winter crop season (sowing in May) with center pivot irrigation, in Santo Antônio de Goiás. The area in which the experiments were set up is routinely used for evaluating the reaction of common bean lines to *Fusarium* wilt, as it is highly infested with the pathogen (D. G. Pereira et al., 2019a; H. S. Pereira et al., 2016, 2018; Torres et al., 2021, 2022). The plots were composed of two 4-m rows in 2012 and 2013 and four 4-m rows in 2014. Sowing density was 12 seeds per meter, with a spacing of 0.45 m between rows. Fertilization and other crop treatments were performed according to recommendations for the crop.

The traits evaluated were reaction to *Fusarium* wilt, grain yield, and 100-seed weight. To evaluate reaction to Fusarium wilt, the scoring scale described by Torres et al. (2021) was used, ranging from 1 to 9, in which

1 represents the absence of susceptible plants; 2: 0.1-5%; 3: 5.1-10%; 4: 10.1-20%; 5: 20.1-40%; 6: 40.1-60%; 7: 60.1-80%; 8: 80.1-90%; and 9: 90.1-100%. The evaluation was performed by two persons at the R8 (grain filling) phenological stage. Hundred-seed weight (g) was determined by weighing a random sample of 100 grains obtained from each plot. Grain yield was determined as the weight of the grains harvested from two rows of the plot converted to kg ha^{-1}.

Individual and joint analyses of variance were performed for each trait, considering the effects of genotypes and years/generation as fixed. For the joint analysis of the experiments, the homogeneity of variances was checked by the Hartley test, observing the ratio between the largest and smallest mean squared residual (C. D. Cruz et al., 2012). Selection accuracy was also estimated to assist in the evaluation of experimental quality (Resende & Duarte, 2007).

The effects of general combining ability of the parents ($\hat{g}_i$ and $\hat{g}_j$) and specific combining ability of the populations ($\hat{s}_{ij}$) were estimated by Method 4 of Griffing (1956) for all the traits evaluated in the diallel analyses. The deviations (σ) were obtained from the square root of the variances of the effects and of the contrasts of general combining ability ($\hat{g}_i - \hat{g}_j$) and specific combining ability ($\hat{s}_{ij} - \hat{s}_{ik}$, $\hat{s}_{ij} - \hat{s}_{kl}$) effects (C. D. Cruz et al., 2012).

The relative contribution of the additive and non-additive effects was analyzed based on the coefficient of determination (R^2, %), estimated by the sum of squares of the general combining ability and specific combining ability, respectively, relative to the sum of squares of the populations (Di Prado et al., 2019; Ferreira et al., 2018). The mean values were compared by the Scott-Knott cluster analysis test ($p \leq 0.05$). Statistical analyses were performed using the Genes program (C. D. Cruz, 2013).

Results and Discussion

Estimates of the coefficient of variation ranged from 11.2% to 16.7% for grain yield and from 4.1% to 6.4% for 100-seed weight, which are close to those obtained by D. G. Pereira et al. (2019a). These values were low, indicating good experimental accuracy. For reaction to *Fusarium* wilt, the estimates of the coefficient of variation were higher, ranging from 17.6% to 26.6%, similar to those found by D. G. Pereira et al. (2019a), H. S. Pereira et al. (2016), and Torres et al. (2021). This can be explained by the facts that *Fusarium oxysporum* f. sp. *phaseoli* is a soil pathogen, with uneven distribution in the area, and that the disease was evaluated in the field. The high experimental accuracy was confirmed by the selection accuracy estimates, which were all greater than 0.72, considered high or very high (Resende & Duarte, 2007). This indicates a high correlation between genotypic and phenotypic values.

Individual and joint analyses revealed differences between the populations for the three traits (Table 1), indicating the existence of genetic variability and the possibility of selection of superior populations. There were differences between years/generations, as confirmed by the wide variation observed between the mean values of the years/generations evaluated: 1,274 to 2,617 kg ha^{-1} for yield, 3.8 to 4.5 for reaction to *Fusarium* wilt, and 21.7 to 24.5 g for 100-seed weight. There was also an interaction effect of the segregating populations with the years/generations, agreeing with the observations of Torres et al. (2021) for all the traits, and of D. G. Pereira et al. (2019a) for grain yield, indicating that the response of the populations for these traits did not coincide between the years/generations. This interaction can be explained by the fact that common bean is a crop that is quite sensitive to environmental variations, as well as by disease incidence, which is affected by the climatic conditions of each year (Azevedo et al., 2015). The genetic correlation between years/generations was positive, significant, and considered intermediate at 0.62+ between the years/generations 2013/F_4 and 2014/F5 and not significant between the years/generations 2012/F_3 and 2013/F_4 (0.32) and 2012/F_3 and 2014/F_5 (0.30), denoting the presence of simple and complex interactions. This finding disagrees with Torres et al. (2021), who obtained a high and significant correlation (> 0.80), suggesting a simple interaction between the evaluated environments. This may indicate the prevalence of different races in the different years/generations.

Table 1
Summary of joint analyses of variance for reaction to *Fusarium* wilt (scores from 1 to 9), grain yield (kg ha^{-1}), and 100-seed weight (g) evaluated in segregating populations in the F_3, F_4, and F_5 generations of carioca common bean in the 2012, 2013, and 2014 winter seasons, respectively

		Reaction to Fusarium wilt			Yield			100-seed weight		
Source of variation	DF	MS	P-value	R^2%	MS	P-value	R^2%	MS	P-value	R^2%
Blocks/Years	6	1.2	-	-	555854	-	-	3.6	-	-
Treatments	22	6.4	0.001	-	317447	0.001	-	10.6	0.001	-
Checks (C)	1	72.0	0.001	-	2361689	0.001	-	1.9	0.263	-
Populations (P)	20	3.5	0.001	-	179637	0.001	-	9.9	0.001	-
GCA	6	6.6	0.001	57	178947	0.016	30	21.8	0.001	66
SCA	14	2.1	0.003	43	179933	0.001	70	4.8	0.001	34
C *vs* P	1	0.6	0.414	-	1029393	0.001	-	33.8	0.563	-
Years/Generations (A)	2	9.9	0.019	-	32053684	0.001	-	137.8	0.001	-
Treatments × A	44	1.7	0.001	-	97706	0.046	-	2.8	0.003	-
Checks × A	2	2.0	0.096	-	80716	0.297	-	7.4	0.008	-
Populations × A	40	1.7	0.002	-	97299	0.053	-	2.5	0.012	-
GCA × A	12	0.8	0.505	-	56556	0.591	-	4.7	0.001	-
SCA × A	28	2.1	0.001	-	114760	0.020	-	1.6	0.375	-
(C *vs* P) × A	2	0.8	0.385	-	122829	0.159	-	3.2	0.118	-
Residue	132	0.8	-	-	65880	-	-	1.5	-	-
Overall mean		4.3			1879			23.3		
CVe (%)		21.4			13.7			5.2		

DF: degrees of freedom; MS: mean square; R^2 (%:) coefficient of determination; CVe: coefficient of variation.

There was a difference regarding the general combining ability (GCA) effects of the parents for reaction to *Fusarium* wilt, yield, and 100-seed weight an indication that some parents were differentiated from the others (Table 1). There were also differences for the specific combining ability (SCA) effects, showing that the lines and the cultivars had degrees of genetic complementation by the contribution in allele frequency at loci with some dominance (C. D. Cruz et al., 2012). Because GCA contributes to the additive effects and SCA to the non-additive effects, this suggests variability for the loci with additive and dominance effects on the expression of the three traits analyzed. In terms of reaction to *Fusarium* wilt, a contribution of the additive effects (R^2 = 57%) and of the non-additive effects (R^2 = 43%) was observed. The contribution of the additive effects was similar to that reported by Torres et al. (2021), who evaluated populations in a partial diallel cross under field conditions without inoculation and described that the proportion of contribution of the additive effects was greater in the two groups of parents (42% and 50%) than the non-additive effects (8%), suggesting greater genetic gains from selection of plants resistant to *Fusarium* wilt. In the presence of additive effects, the alleles are fixed as selfing generations advance, thereby allowing selection in early stages for alleles that provide increased resistance to *Fusarium* wilt and contributing to the efficiency of breeding programs.

Populations with better mean values, additive genetic effects, and a high frequency of favorable alleles are expected in crosses involving parents with high GCA effects (Moura et al., 2018). With respect to reaction to *Fusarium* wilt, the $\hat{g}_i$ estimates were statistically negative for four parents: BRS Notável showed the greatest effect of $\hat{g}_i$ (-0.51), which was greater than those of CNFC 15872 (-0.20), IPR Juriti (-0.18), and BRSMG Talismã (-0.13) (Table 2), suggesting that these parents produce the most resistant populations. The negative $\hat{g}_i$ effects for reaction to Fusarium wilt indicate that the parents produce progeny with increased resistance to *Fusarium* wilt. These elite lines and cultivars originated from different crosses, which may suggest that the resistance alleles of these cultivars are different. Therefore, BRS Notável is the cultivar that most contributed to producing more resistant populations. This tendency was observed in two of the three environments evaluated, which confirms that this cultivar is one of the carioca grain cultivars with the highest level of resistance to *Fusarium* wilt, as well as the most stable (H. S. Pereira et al., 2016).

Table 2
Estimates of general combining ability (*gi*) effects based on joint analysis of the parents for reaction to *Fusarium* wilt (scores from 1 to 9), yield (kg ha^{-1}), and 100-seed weight (g) evaluated in segregating populations of carioca common bean in the F_3, F_4, and F_5 generations in the 2012, 2013, and 2014 winter seasons, respectively

Parent	Reaction to Fusarium wilt	Yield	100-seed weight
BRS Notável	-0.51*	87.90*	0.23*
CNFC 15872	-0.20*	-95.32*	-0.41*
IPR Juriti	-0.18*	-34.68	0.99*
BRSMG Talismã	-0.13*	-14.06	-0.02
BRS Requinte	0.09	72.01*	-1.24*
BRS Ametista	0.27*	5.03	0.06
Pérola	0.67*	-20.88	0.39*
$\hat{\sigma}(\hat{g}_i)$	0.13	35.42	0.17
$\hat{\sigma}(\hat{g}_i - \hat{g}_j)$	0.19	54.11	0.26

$\hat{\sigma}(\hat{g}_i)$: standard deviation associated with the $\hat{g}_i$ effect of the parent; $\hat{\sigma}_{(\hat{g}_i - \hat{g}_j)}$: standard deviation associated with the contrast between the parents.

Cultivars Pérola and BRS Ametista contributed to the formation of less resistant populations (Table 2); however, some of the populations obtained from the combination of these parents showed good yield and 100-seed weight. Cultivar Pérola is considered by farmers as a standard of tolerance to root diseases such as Fusarium wilt and root rots (Fusarium solani and Rhizoctonia solani) in common bean, since it achieves good yields even when showing symptoms of these diseases.

The combination of the parents allows for estimating the SCA effects in the populations ($\hat{s}_{ij}$). Considering the $\hat{s}_{ij}$ effects for reaction to Fusarium wilt (Table 3), four populations exhibited statistically negative estimates: Pérola / IPR Juriti (-1.06), BRSMG Talismã / BRS Requinte (-0.44), BRS Ametista / BRSMG Talismã (-0.39), and BRS Notável / BRS Requinte (-0.28), indicating that the four crosses were better than expected based on the GCA of the parents.

Table 3

Mean values and estimates of specific combining ability ($\hat{s}_{ij}$) effects of the segregating populations of carioca common bean as obtained from joint analyses of variance for reaction to *Fusarium* wilt (FW, scores from 1 to 9), grain yield (YIELD, kg ha^{-1}), and 100-seed weight (100SW, g)

Treatment	FW		$\hat{s}_{ij}$	YIELD		$\hat{s}_{ij}$	100SW		$\hat{s}_{ij}$
BRS Notável	2.44	a	-	2013	a	-	22.3	c	-
BRS Notável / CNFC 15872	3.44	b	-0.13	1868	b	-86.2*	24.2	b	-0.41*
BRS Notável / BRS Requinte	3.56	b	-0.28*	2016	a	-44.3	22.1	c	-0.27
BRS Notável / IPR Juriti	3.56	b	0.01	2093	a	199.5*	22.3	c	-0.90*
Pérola / IPR Juriti	3.67	b	-1.06*	1770	b	-14.4	23.0	c	-0.42*
BRS Ametista / BRS Notável	3.78	b	-0.24	2200	a	206.1*	24.1	b	0.36*
BRSMG Talismã / BRS Requinte	3.78	b	-0.44*	1954	a	-4.4	21.7	c	-0.41*
IPR Juriti / CNFC 15872	3.78	b	-0.10	1647	c	-123.9*	24.7	a	0.74*
BRS Notável / BRSMG Talismã	3.89	b	0.27*	1788	b	-186.4*	23.7	b	0.10
BRS Ametista / BRSMG Talismã	4.00	b	-0.39*	2081	a	189.4*	23.6	b	0.18
BRS Ametista / CNFC 15872	4.11	c	-0.24	1820	b	-50.6	24.3	b	-0.12
BRSMG Talismã / CNFC 15872	4.22	c	0.27*	1854	b	2.1	24.1	b	-0.22
BRS Requinte / CNFC 15872	4.44	c	0.27*	2059	a	121.0*	22.6	c	-0.58*
BRS Ametista / BRS Requinte	4.44	c	-0.17	1817	b	-161.1*	23.2	c	0.95*
BRSMG Talismã / IPR Juriti	4.44	c	0.52*	1804	b	12.4	23.1	c	0.16
BRS Ametista / IPR Juriti	4.56	c	0.23	1655	c	-155.4*	23.2	c	0.11
BRS Requinte / IPR Juriti	4.56	c	0.41*	1959	a	81.8*	22.1	c	0.31
Pérola / BRSMG Talismã	4.56	c	-0.24	1853	b	-13.1	24.0	b	0.20
Pérola / CNFC 15872	4.67	c	-0.08	1983	a	137.6*	25.4	a	0.59*
BRS Notável / Pérola	4.78	c	0.36*	1879	b	-88.7*	25.1	a	1.12*
Pérola / BRS Requinte	5.22	d	0.21	1959	a	7.0	22.5	c	0.00
BRS Ametista / Pérola	6.00	e	0.81*	1856	b	-28.4	22.4	c	-1.49*
BRS Cometa	6.44	e	-	1288	d	-	21.6	c	-
$\hat{\sigma}(\hat{s}_{ij})$			0.25			69.9			0.33
$\hat{\sigma}(\hat{s}_{ij} - \hat{s}_{ik})$			0.39			187.4			0.51
$\hat{\sigma}(\hat{s}_{ij} - \hat{s}_{kl})$			0.33			93.7			0.44

$\hat{\sigma}(\hat{s}_{ij})$: standard deviation associated with the effect of $\hat{s}_{ij}$ of the segregating population; $\hat{\sigma}(\hat{s}_{ij} - \hat{s}_{ik})$, $\hat{\sigma}(\hat{s}_{ij} - \hat{s}_{kl})$: standard deviation associated with the contrast between segregating populations; mean values followed by the same letter do not differ statistically from each other by the Scott-Knott test at 5% probability.

Negative and significant $\hat{s}_{ij}$ effects for reaction to *Fusarium* wilt, especially when associated with low mean values and with at least one parent with a favorable $\hat{g}_i$ estimate, indicate the potential of populations for obtaining superior lines (C. D. Cruz et al., 2012; Torres et al., 2021). The mean values of the populations ranged from 3.44 to 6.00 (Table 3). Cultivar BRS Notável (2.44) exhibited the lowest mean, confirming its high resistance (H. S. Pereira et al., 2016), whereas BRS Cometa (6.44) showed the highest mean, confirming its high susceptibility (H. S. Pereira et al., 2016, 2018). No population displayed a mean resistance score similar to that of BRS Notável, which was to be expected, since the populations are still segregating. However, among the nine populations clustered in the second group, BRS Notável / CNFC 15872 (3.44b), BRS Notável / IPR Juriti (3.56b), and IPR Juriti / CNFC 15872 (3.78b) not only showed high resistance, but had both parents with high g_i estimates that were statistically negative. Populations BRS Notável / BRS Requinte (3.56b), Pérola / IPR Juriti (3.67b), BRSMG Talismã / BRS Requinte (3.78b), and BRS Ametista / BRSMG Talismã (4.00b) also proved to be promising for resistance to *Fusarium* wilt, because in addition to high resistance, they exhibited statistically negative $\hat{s}_{ij}$ estimates and derived from at least one parent with a statistically negative g_i estimate.

In addition to disease resistance, yield and 100-seed weight are extremely important for the production and sale of common bean. For grain yield, a contribution of the non-additive effects (R^2 = 70%) and additive effects (R^2 = 30%) was observed (Table 1), in a way similar to that observed by Machado et al. (2002). The smaller proportion of the additive effect can be explained by the fact that the seven parents were cultivars or lines that had been previously selected for yield, showing lower variability of alleles between the parents (C. D. Cruz et al., 2012; Machado et al., 2002).

The highest $\hat{g}_i$ effects that were statistically positive for grain yield were observed for cultivars BRS Notável (87.9) and BRS Requinte (72.0) (Table 2). The highest-yielding populations exhibited mean values from 1,954 to 2,200 kg ha^{-1} (Table 3), forming a group that includes cultivar BRS Notável (2,013 kg ha^{-1}) and nine populations. The lowest mean yield was that of cultivar BRS Cometa (1,288 kg ha^{-1}), which is susceptible to Fusarium wilt, as previously mentioned.

Six populations showed statistically positive s_{ij} estimates for yield, namely, BRS Ametista / BRS Notável (206.1), BRS Notável / IPR Juriti (199.5), BRS Ametista / BRSMG Talismã (189.4), Pérola / CNFC 15872 (137.6), BRS Requinte / CNFC 15872 (121.0), and BRS Requinte / IPR Juriti (81.8) (Table 3). Among the nine populations with high mean values, BRS Ametista / BRS Notável (2,200 kg ha^{-1}), BRS Notável / IPR Juriti (2,093 kg ha^{-1}), BRS Requinte / CNFC 15872 (2,059 kg ha^{-1}), and BRS Requinte / IPR Juriti (1,959 kg ha^{-1}) had at least one of the parents with statistically positive estimates of $\hat{g}_i$ effects, as well as statistically positive estimates of $\hat{s}_{ij}$ effects for grain yield (Table 3). These estimates suggest the superiority of these populations for grain yield compared with the other populations evaluated.

For 100-seed weight, there was contribution of additive effects (R^2 = 66%) and non-additive effects (R^2 = 34%) in the populations (Table 1). Among the parents, three displayed statistically positive g_i estimates: IPR Juriti (0.99), Pérola (0.39), and BRS Notável (0.23) (Table 2), with superiority of IPR Juriti over the others. Therefore, IPR Juriti is that which most contributes to the frequency of favorable alleles to increase 100-seed weight in the populations. These three cultivars can be used in crosses aiming at increasing one of the most commercially relevant characteristics, i.e. grain size (N. D. Ribeiro et al., 2019). Plant breeding has contributed to the generation of cultivars with larger-sized beans, considering that high-yielding cultivars have small grains, which are not attractive to the consumer (Santos et al., 2022). Populations BRS Notável / Pérola (1.12), BRS Ametista / BRS Requinte (0.95), IPR Juriti / CNFC 15872 (0.74), Pérola / CNFC 15872 (0.59), and BRS Ametista / BRS Notável (0.36) (Table 3) exhibited statistically positive s_{ij} estimates.

Three groups of mean values were formed for 100-seed weight. The highest mean values were those of populations Pérola / CNFC 15872 (25.4), BRS Notável / Pérola (25.1), and IPR Juriti / CNFC 15872 (24.7) (Table 3). These three populations not only exhibited high mean values, but also statistically high s_{ij} estimates and at least one parent with a statistically positive g_i estimate. In addition to these, seven other populations formed the second group of mean values, consisting of BRS Ametista / CNFC 15872 (24.3), BRS Notável / CNFC 15872 (24.2), BRS Ametista / BRS Notável (24.1), BRSMG Talismã / CNFC 15872 (24.1), Pérola / BRSMG Talismã (24.0), BRS Notável / BRSMG Talismã (23.7), and BRS Ametista / BRSMG Talismã (23.6). Approximately 48% of the populations exceeded the mean value of BRS Notável (22.3), which was in the group of lower mean values. Thus, these populations are also promising for obtaining lines with 100-seed weight within the commercial standard. Among the populations clustered in the second group, BRS Ametista / BRS Notável showed a statistically positive s_{ij} estimate and also had one of the parents with the highest statistically positive g_i estimates.

Considering the three traits in relation to BRS Notável, the resistant check cultivar, no population was superior for reaction to *Fusarium* wilt. This cultivar not only has high resistance to *Fusarium* wilt, but is also resistant to anthracnose (*Colletotrichum lindemuthianum*) and diseases such as common bacterial blight (*Xanthomonas axonopodis* pv. *phaseoli*) and bacterial wilt (*Curtobacterium flaccumfaciens* pv. *flaccumfaciens*) (H. S. Pereira et al., 2012). For grain yield, nine populations showed similar mean values. As for 100-seed weight, 10 populations exceeded the mean of BRS Notável.

Populations BRS Notável / CNFC 15872, BRS Ametista / BRS Notável, and BRS Notável / BRSMG Talismã have at least one parent with a good estimate of general combining ability for all the traits evaluated, and the same is true for the population of BRS Ametista / BRSMG Talismã regarding reaction to *Fusarium* wilt. These populations are among the most resistant to Fusarium wilt, having good yield and 100-seed weight (Table 3). The four populations are simultaneously promising for obtaining superior lines for resistance to *Fusarium* wilt, yield, and 100-seed weight, because in addition to good mean values, they have at least one parent with a good estimate of general combining ability for the traits.

Conclusions

Additive and non-additive effects are important in the genetic control of reaction to Fusarium wilt, yield, and 100-seed weight in common bean.

Cultivar BRS Notável is recommended as a parent for producing populations of carioca common bean that comprise greater resistance to *Fusarium* wilt, yield, and 100-seed weight.

Populations BRS Notável / CNFC 15872, BRS Ametista / BRS Notável, BRS Notável / BRSMG Talismã, and BRS Ametista / BRSMG Talismã are the most promising for obtaining carioca common bean lines with high resistance to *Fusarium* wilt, high yield, and greater 100-seed weight.

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