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Genetic parameters and selection of carioca common bean lines resistant to fusarium wilt

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Abstract – The objective of this work was to estimate genetic parameters and to select lines of carioca commercial bean group with high yield, great 100-seed weight, good grain appearance, and good resistance to fusarium wilt, disease caused by the fungus *Fusarium oxysporum* f. sp. *phaseoli* that inhabits the soil. A total of 114 lines coming from two populations were evaluated together with seven control genotypes in the winter crop season in the years/generations of 2015/$F_{5:7}$ and 2016/$F_{5:8}$. There is a genetic variability among the carioca common bean (*Phaseolus vulgaris*) lines for all the traits evaluated, and the estimates of the genetic parameters show a possible successful selection for reaction to fusarium wilt, yield, grain appearance, and 100-seed weight. Twenty-four lines of carioca common bean that were selected combine high resistance to fusarium wilt, yield, 100-seed weight, and good grain appearance. CNFC 19126, CNFC 19205, and CNFC 19131 show a better performance than the control genotypes with the highest level of resistance, so their evaluation in multiple environments is recommended, aiming at new resistant cultivars to *Fusarium oxysporum* f. sp. *phaseoli*.

Index terms: *Fusarium oxysporum* f. sp. *phaseoli*, *Phaseolus vulgaris*, 100-seed weight, bean grain appearance, yield.

Parâmetros genéticos e seleção de linhagens de feijão-carioca resistentes à murcha-de-fusário

Resumo – O objetivo deste trabalho foi estimar parâmetros genéticos e selecionar linhagens de grupo de feijão comercial carioca com alta produtividade, grande massa de 100 grãos, bom aspecto visual dos grãos e boa resistentência à murcha-de-fusário, doença causada pelo fungo *Fusarium oxysporum* f. sp. *phaseoli* que habita o solo. Um total de 114 linhagens obtidas de duas populações foram avaliadas juntamente com sete genótipos controles na safra de inverno nos anos/gerações de 2015/$F_{5:7}$ e 2016/$F_{5:8}$. Há variabilidade genética entre as linhagens de feijão carioca (*Phaseolus vulgaris*) para todos os caracteres avaliados, e as estimativas de parâmetros genéticos mostram uma possível seleção bem-sucedida para reação à murcha-de-fusário, produtividade, aparência dos grãos e massa de 100 grãos. Vinte e quatro linhagens de feijão carioca que foram selecionadas combinam alta resistência à murcha-de-fusário, produtividade, massa de 100 grãos e boa aparência. CNFC 19126, CNFC 19205 e CNFC 19131 destacaram-se porque eles apresentam um melhor desempenho que os genótipos de controle com o maior nível de resistência, portanto sua avaliação em vários ambientes é recomendada, visando a novas cultivares resistentes a *Fusarium oxysporum* f. sp. *phaseoli*.

Termos para indexação: *Fusarium oxysporum* f. sp. *phaseoli*, *Phaseolus vulgaris*, massa de 100 grãos, aspecto visual dos grãos, produtividade.

Introduction

Common bean (*Phaseolus vulgaris* L.) is an important source of protein for human nutrition, consequently, its average yield practically tripled over the last 35 years in Brazil, from 514 in 1985 to 1,463 kg ha^{-1} in 2021 (Embrapa Arroz e Feijão, 2022). Brazil is one of the largest producers of this crop, with an annual production of 2.4 million tons, in which the carioca commercial type bean represents 75% of the market (Pereira et al., 2021; Embrapa Arroz e Feijão, 2022). The increase in yield may be explained by the development of new cultivars resistant to the main bean diseases; however, there is not a large number of cultivars with a good level of resistance to some diseases, such as fusarium wilt (Pereira et al., 2016, 2018), which is caused by the soil fungus *Fusarium oxysporum* f. sp. *phaseoli*.

Fusarium wilt occurs throughout Brazil, causing losses of up to 80% in common bean yield (Pereira et al., 2008), especially in the Midwest region of Brazil during the winter crop season, with sowing from May to June, which represents 26% of Brazilian production of common bean (Embrapa Arroz e Feijão, 2022). Despite the high use of technology during this crop season, including center pivot irrigation (Batista et al., 2017; Pereira et al., 2019), it combines mild temperature and moisture conditions that favor the development of the pathogen.

For a successful selection of common bean genotypes, it is important to select genetic parameters that react to fusarium wilt, allowing estimation of the proportion of the phenotype explained by the genotype (Torres et al., 2022). Nevertheless, the estimates of genetic parameters for resistance to fusarium wilt are restricted to studies conducted in controlled environments, with inoculation of the pathogen (Cândida et al., 2009; Musoni et al., 2010; Pereira et al., 2011; Leitão et al., 2020). The results obtained in these studies have shown heritability ranging from 72.0 to 99.6%, with predominance of high estimates (Pereira et al., 2009; Musoni et al., 2010; Pereira et al., 2011), and estimates of gains expected from selection from 27 to 36% (Cândida et al., 2009).

The estimation of these parameters and the evaluation of different lines under field conditions are essential for the selection and recommendation of cultivars. Recently, Torres et al. (2022) obtained heritability estimates for reaction to fusarium wilt in black bean lines evaluated in a field infested with the pathogen and obtained high estimates, ranging from 86 to 93%.

In addition to disease resistance, other traits are important in carioca common bean lines, such as high yield and grains with commercial standard of size and appearance, which is very light beige seed coat color with light brown steaks (Pereira et al., 2012a; Faria et al., 2013). Simultaneous selection for the traits is indispensable, since cultivars must show superiority for a set of important agronomic traits. Some studies have shown the effectiveness of this method of selection (Maziero et al., 2015; Alvares et al., 2016; Torres et al., 2022), including selection for reaction to fusarium wilt.

The objective of this work was to estimate genetic parameters and select carioca common bean lines resistant to fusarium wilt, as well as with high yield, good appearance, and great 100-seed weight under conditions of natural infestation of the pathogen in the field.

Materials and Methods

The experiment was carried out in the municipality of Santo Antônio de Goiás, in the state of Goiás, Brazil (16º30'17"S, 49º16'53"W, at 819 m of altitude). The region has an Aw, tropical savanna, megathermal climate, according to Köppen-Geiger's classification. The predominant soil is a Latossolo Vermelho-Ácrico, according to the Brazilian soil classification system (Santos et al., 2018), which corresponds to a positively charged Oxisol.

Two segregating populations were used to obtain the lines: 'BRS Notável'/'BRS Ametista' and 'BRS Notável'/CNFC 15872, which were selected among 21 populations of carioca grain type, evaluated in a diallel cross in the generations/years of F_3/2012, F_4/2013, and F_5/2014 in an area infested by the pathogen during the winter crop season sowed in May, as they presented high resistance to fusarium wilt, high yield, and high 100-seed weight (Cavalheiro, 2021). From each population of the F_5 generation, 57 individual plants were collected, giving rise to the lines. The harvested seeds were used for multiplication during the rainy crop season of 2014, sowed in December.

The 114 lines were evaluated in the winter crop season, sowed in May, in the years/generations of

2015/$F_{5:7}$ and 2016/$F_{5:8}$, together with seven control genotypes: 'BRS Ametista', 'BRS Notável', CNFC 15872, and 'Pérola', which have different levels of resistance; as well as 'BRS Sublime', 'BRS 9435 Cometa', and 'BRS Estilo', which are susceptible to fusarium wilt (Pereira et al., 2012b, 2016, 2018; Batista et al., 2016).

The experiments were conducted in an 11 × 11 triple lattice, with center pivot irrigation. The area where the experiments were conducted is routinely used to evaluate the reaction of common bean lines/cultivars to fusarium wilt, since it is highly infested by the pathogen (Pereira et al., 2016, 2018, 2019; Torres et al., 2021, 2022). The plots consisted of two rows with 3.0 m, spacing of 0.5 m between rows, and sowing density of 12 seeds per meter. Fertilization was carried out with 200 kg ha^{-1} monoammonium phosphate (10% N and 50% P_2O_5) at sowing and 178 kg ha^{-1} urea (80 kg ha^{-1} N) as topdressing at 20 days after planting. Other cultural practices, such as weed and insect control, were performed whenever necessary; however, no pesticides were applied for disease control, as performed by Torres et al. (2022).

The variables reaction to fusarium wilt, yield, and 100-seed weight were evaluated during the years of 2015 and 2016, while grain appearance was evaluated only in 2015. For reaction to fusarium wilt, a scoring scale ranging from 1 (resistant) to 9 (susceptible) was used, in which score 1 represents absence of susceptible plants; score 2, 0.1 to 5.0%; score 3, 5.1 to 10.0%; score 4, 10.1 to 20.0%; score 5, 20.1 to 40.0%; score 6, 40.1 to 60.0%; score 7, 60.1 to 80.0%; score 8, 80.1 to 90.0%; and score 9, 90.1% to 100.0% (Torres et al., 2022).

Evaluations were made by two evaluators in the R_8 phenological phase, or grain filling. Grain yield was obtained from the weight of the grain harvested from each plot, followed by transformation to kg ha^{-1}. For 100-seed weight in grams, a random sample of 100 beans obtained from each plot was weighed. Grain appearance was evaluated 60 days after harvest in a random sample of 50 grains of each plot, through a scoring scale ranging from 1 to 5, adapted from Faria et al. (2013), in which score 1 refers to the typical carioca bean, with a very light beige seed coat, light brown streaks, and a non-flattened shape, while score 5 refers to a very dark beige seed coat, dark brown streaks, a yellow halo, and beans of a flattened shape.

Individual analyses of variance were used on the data for the four traits, and joint analyses of variance, for reaction to fusarium wilt, yield, and 100-seed weight. The effect of genotypes was considered random and that of environments fixed. For joint analysis of the experiments, the homogeneity of the variances was checked by the Hartley's test (Ramalho et al., 2012). Selective accuracy was estimated to assist the evaluation of the experimental quality.

The following genetic parameters were estimated: genetic variance (σ^2_g), phenotypic variance (σ^2_f), heritability at mean level (h^2), expected gain from direct and simultaneous selection, and genetic correlations among the traits (r_g) (Ramalho et al., 2012). The expected gains from direct selection and simultaneous selection were obtained considering the selection intensity of 21%. Thus, 24 superior lines were selected considering the two populations together, and 12 superior lines within each population.

In order to estimate the direct gain, the best lines were selected for each trait. For simultaneous selection, which considers all traits, the multiplicative index was used for selecting the best lines, considering a pre-established minimum or maximum value for the variables. The lines that did not reach at least one trait were eliminated. The lines were selected based on the overall mean values of each trait. In selection based on joint analysis, the lines selected had scores below 4.0 for reaction to fusarium wilt, mean yield higher than 2,069 kg ha^{-1}, 100-seed weight higher than 22.2 g per 100 seeds, and score below 3.6 for grain appearance. The genetic correlation coefficients among the traits were estimated with the mean values of the lines for each trait, with the bootstrap test for evaluation of significance. Statistical analyses were performed on the Genes program (Cruz, 2013).

Results and Discussion

The efficiency of the lattice was superior to 100% for all the traits studied, indicating that the lattice design was more efficient than the randomized block design (Table 1). For reaction to fusarium wilt, the estimates of the coefficient of variation ranged from 26 to 31% in the individual analyses, being similar to those observed by Pereira et al. (2016, 2019), Borba et al. (2017), and Torres et al. (2021, 2022). These estimates can be explained by the fact that *Fusarium* *oxysporum* f. sp. *phaseoli* is a soil pathogen, which is not necessarily uniformly distributed in the soil, and evaluation of the disease was made in the field under natural conditions of occurrence. Similar estimates were also observed by Pereira et al. (2008, 2011) and Cândida et al. (2009) with inoculation of the pathogen under controlled conditions. Nevertheless, the high contribution of the genetic component in expression of the phenotype, observed by the high selective accuracy estimates in the individual analyses (0.77 and 0.85), indicates high correlation between the genotypic and phenotypic values.

The estimates of the coefficient of variation in the individual analyses for yield (16 and 17%), 100-seed weight (5.6 and 7.3%), and grain appearance (14.5%) (Table 1) showed good experimental accuracy, similar to that observed by Alvares et al. (2016), Pereira et al. (2018, 2019), and Nagel et al. (2020). The estimates of selective accuracy were 0.83 for yield in the two years, 0.92 and 0.86 for 100-seed weight, and 0.80 for grain appearance, confirming good accuracy.

In the individual analyses of variance, the effects of the lines were significant for the four traits in the two experiments. This also occurred in the joint analyses (Table 1), indicating that there was variability and the possibility of selecting lines with a higher degree of resistance to fusarium wilt, yield, and 100-seed weight, as well as better grain appearance.

During the years of the study, there were significant effects on the three traits (Table 1): yield of 2,172 and 2,327 kg ha^{-1}, reaction to fusarium wilt with scores 3.5 and 4.5, and 100-seed weight of 26.1 and 21.1 g, in 2015 and 2016, respectively. There was an interaction between genotypes and environments for yield, as frequently reported by other studies (Faria et al., 2013; Pereira et al., 2018; Torres et al., 2021, 2022), and for 100-seed weight, which is in agreement with Alvares et al. (2016), Pereira et al. (2017), Ribeiro et al. (2018), and Torres et al. (2021, 2022).

Nevertheless, there are also reports of no interaction between genotypes and environments (Di Prado et al., 2019), for fusarium wilt, for instance, the interaction

Table 1. Summaries of joint analyses of variance for reaction to fusarium wilt, yield, 100-seed weight, and individual analysis for grain appearance, evaluated in carioca common bean (*Phaseolus vulgaris*) genotypes in the winter crop season of 2015 and 2016, in the municipality of Santo Antônio de Goiás, in the state of Goiás, Brazil.

Source of variation[(1)]	DF[(2)]	Reaction to *Fusarium* wilt (scores from 1 to 9)		Yield (kg ha^{-1})		100-seed weight (g)		Grain appearance (scores from 1 to 5)	
		MS	p-value	MS	p-value	MS	p-value	MS	p-value
Genotypes (G)	120	6.47	0.001	589,266	0.001	18.7	0.001	0.68	0.001
Control genotypes (C)	6	15.82	0.001	1,497,692	0.001	17.3	0.001	1.08	0.001
Lines (L)	113	5.54	0.001	514,992	0.001	18.8	0.001	0.65	0.001
L1	56	3.15	0.001	435,144	0.001	11.8	0.001	0.62	0.001
L2	56	8.04	0.001	593,664	0.001	26.0	0.001	0.63	0.001
L1 vs L2	1	0.01	0.921	580,874	0.044	2.6	0.283	3.96	0.001
C vs L	1	54.71	0.001	3,531,663	0.001	24.3	0.001	1.76	0.007
Environment (E)	1	169.70	0.001	4,355,734	0.001	4,541.5	0.001	-	-
G × E	120	1.58	0.082	318,933	0.001	3.3	0.003	-	-
C × E	6	0.75	0.745	258,087	0.097	2.0	0.499	-	-
L × E	113	1.62	0.060	322,262	0.001	3.4	0.002	-	-
L1 × E	56	1.42	0.310	250,830	0.001	3.4	0.012	-	-
L2 × E	56	1.83	0.033	360,134	0.001	2.8	0.115	-	-
(L1 vs L2) × E	1	1.60	0.267	2,201,670	0.001	36.7	0.001	-	-
(C vs L) × E	1	1.40	0.299	307,773	0.143	0.0	0.906	-	-
Mean effective error	420	1.30		142,950		2.2		0.24	
Efficiency of the lattice		107.4		114.7		109.2		107.9	
Overall mean		4.0		2,249.3		23.6		3.4	
CVe (%)[(3)]		28.3		16.8		6.3		14.5	

[(1)]L1, 'BRS Notável'/'BRS Ametista' population; L2, 'BRS Notável'/CNFC 15872 population. [(2)]DF, degrees of freedom; MS, mean square. [(3)]CVe, coefficient of variation.

was not significant, indicating that the performance of the lines was similar in the two years, as observed by Pereira et al. (2019) and Torres et al. (2022), who evaluated segregating populations and lines of black bean, respectively, in the same experimental area in the winter crop season in a period from 2012 to 2016. The lack of interaction indicates that the studied area has one or few races of the pathogen, or that one race is prevalent over time. In addition, the genetic correlation between the lines in the two environments was high and positive (r_g=0.91^{++}), which corroborates this hypothesis, also confirmed in the studies of Torres et al. (2021, 2022).

There are, at least, seven races of the pathogen described until the moment (Henrique et al., 2015); however, the systems used to define these races vary, including different manners of evaluation and different series of cultivars (Henrique et al., 2015), which hinders understanding its pathogenic variability. For that reason, there are few studies on the prevalence of races in the main common bean producing regions, making it difficult to develop cultivars with broad resistance (Torres et al., 2022). Therefore, the result obtained in the present study may also indicate that the reaction to fusarium wilt is controlled by few genes or by loci of quantitative traits of great effect, as observed by Cândida et al. (2009) and Batista et al. (2017) in studies conducted under controlled conditions.

The reaction to fusarium wilt mean scores of the 114 lines based on joint analysis ranged from 2.4 for the line CNFC 19206 to 6.9 for the line CNFC 19199, both belonging to the same population ('BRS Notável'/CNFC 15872), and 22% of the lines had greater resistance than the most resistant control genotype ('BRS Notável' = 3.2). All the 114 lines were more resistant than the most susceptible control genotype ('BRS Estilo' = 6.9 and 'BRS Cometa' = 7.7), which confirms the merit of the selected populations (Cavalheiro, 2021).

The presence of genetic variation, confirmed by the estimates of genetic difference different from zero and of high estimates of heritability, confirmed the high variation of a genetic nature (Table 2). The heritability estimates were of moderate magnitude, 51 and 66%, in the two environments and also in the joint analysis, 77%; though they were inferior to the estimate obtained by Torres et al. (2022) of 91% when evaluating black bean lines in an infested field with *F. oxysporum* f. sp. *phaseoli*. The estimates of heritability obtained in this study are compatible with those obtained in studies performed under controlled conditions of 72.0 to 99.6% (Cândida et al., 2009; Musoni et al., 2010; Pereira et al., 2011; Leitão et al., 2020). The heritability estimates indicate that it is possible to obtain high genetic gains from selection of lines within the populations for reaction to fusarium wilt. The 'BRS Notável'/CNFC 15872 population had the highest heritability estimate, which was 83.9%.

The selection of superior genotypes increases the frequency of favorable alleles, increasing the probability of more resistant extreme genotypes. Thus, the genetic gain was estimated from direct selection of 24 lines, which increased the resistance to fusarium wilt in 23% (Table 3). The mean of the 24 lines selected was similar to that of the genotype ‘BRS Notável’, the standard of resistance to fusarium wilt in carioca common bean (Pereira et al., 2016), indicating the good level of resistance of the lines. Among the 24 lines selected, 15 came from the 'BRS Notável'/CNFC 15872 population, which was supposed to have the highest estimates of the genetic parameters (Table 2). Considering the selection of 12 lines within each population, the gain was of 15.0% in the 'BRS Notável'/'BRS Ametista' population and of 28.1% for 'BRS Notável'/CNFC 15872 one.

For grain yield, the mean values of the 114 lines based on joint analysis ranged from 1,545 for CNFC 19199 to 2,889 kg ha^{-1} for CNFC 19226, both belonging to the 'BRS Notável'/CNFC 15872 population, while 19% of the lines had greater yield than the genotype 'BRS Ametista', the control genotype that had the highest yield and also moderate resistance to fusarium wilt. The genetic variance estimated was different from zero and the heritability was high, of 72% (Table 2), which corresponds to what was reported by Pereira et al. (2008) and Torres et al. (2022), indicating genetic variability.

The expected gain from direct selection of the 24 lines was 12.3% for grain yield, higher than the 10.8% obtained by Torres et al. (2022), with selection intensity of 26.7%, and lower than that observed by Maziero et al. (2015). However, the latter authors used greater selection intensity of 10%, obtaining gain relative to the smaller number of lines selected. The number of lines among the 24 selected was similar in the two populations (Table 3). Considering the selection in each population, the gain was greater in the population

'BRS Notável'/CNFC 15872 (14.4%), which can be explained by the greater amplitude of the means and heritability (Table 2).

In relation to 100-seed weight, the overall mean of the lines, based on joint analysis, was 24 g (Table 1), near the commercial standard (Pereira et al., 2012a). The variation among the 114 lines was from 19.6 g for CNFC 19179 to 28.2 g for CNFC 19235, both belonging to the 'BRS Notável'/CNFC 15872 population. Twenty-nine percent of the lines were superior to the 'Pérola' genotype, the control genotype with optimal grain size and the commercial reference for that trait (Pereira et al., 2012a, 2012b). The heritability estimated for 100-seed weight was high, of 88.1% (Table 2), consistent with that reported by Alvares et al. (2016) and Ribeiro et al. (2018), which confirms the possibility of obtaining gains from selection. The expected gain from direct selection of the 24 lines was 9.6% (Table 3), near of that reported by Torres et al. (2022): 8.8%.

Among the 24 lines selected, 17 were of the 'BRS Notável'/CNFC 15872 population, indicating the greater potential of this population for 100-seed weight (Table 3). Considering selection within each population, 'BRS Notável'/CNFC 15872 also exhibited the greatest gain, of 11.4%. The selection of the 24 lines resulted in a higher mean value (25.9 g) than that of the 'Pérola' genotype (24.5 g), indicating the considerable potential of the lines.

Grain appearance, a market requirement for the carioca common bean, is of great acceptance by consumers, which is a cream-colored seed coat with brown streaks and an oval-shaped bean (Faria et al.,

Table 2. Estimates of genetic parameters based on joint analyses for reaction to fusarium wilt, yield, 100-seed weight, and grain appearance obtained from carioca common bean (*Phaseolus vulgaris*) lines evaluated in the winter crop season of 2015 and 2016, in the municipality of Santo Antônio de Goiás, in the state of Goiás, Brazil[1].

Lines[2]	Reaction to *Fusarium* wilt (scores from 1 to 9)				Yield (kg ha^{-1})				100-seed weight (g)				Grain appearance (scores from 1 to 5)			
	σ^2_g	σ^2_f	h^2(%)	σ^2_{ga}	σ^2_g	σ^2_f	h^2(%)	σ^2_{ga}	σ^2_g	σ^2_f	h^2(%)	σ^2_{ga}	σ^2_g	σ^2_f	h^2(%)	σ^2_{ga}
Total of lines	0.7	0.9	76.6	0.05	62,007	85,832	72.2	29,885	2.8	3.1	88.1	0.19	0.14	0.22	63.1	-
Pop 1	0.3	0.5	58.8	0.02	48,699	72,524	67.1	17,980	1.6	2.0	81.1	0.19	0.13	0.21	60.9	-
Pop 2	1.1	1.3	83.9	0.09	75,119	98,944	75.9	36,197	4.0	4.3	91.4	0.09	0.13	0.21	61.8	-

[1]σ^2_g, genetic variance; σ^2_f, phenotypic variance; σ^2_{ga}, variation of the genotype by environment interaction; h^2, heritability. [2]Pop 1, 'BRS Notável'/'BRS Ametista' population; Pop 2, 'BRS Notável'/CNFC 15872 population.

Table 3. Mean values of the lines selected, estimates of gain expected from direct selection and simultaneous selection of lines, and number of lines of each population based on joint analyses for reaction to fusarium wilt, yield, 100-seed weight, and grain appearance, obtained from carioca common bean (*Phaseolus vulgaris*) lines evaluated in the winter crop season of 2015 and 2016, in the municipality of Santo Antônio de Goiás, in the state of Goiás, Brazil[1].

Lines[2]	Reaction to *Fusarium* wilt (scores from 1 to 9)			Yield (kg ha^{-1})			100-seed weight (g)			Grain appearance (scores from 1 to 5)			
	Xs	GS(%)	NL	Xs	GS(%)	NL	Xs	GS(%)	NL	Xs	GS(%)	NL	NL
Direct selection													
Lines	2.8	-23.0	24	2,651	12.3	24	26.2	9.6	24	2.8	-10.5	24	-
Pop 1	2.9	-15.0	9	2,641	10.1	13	25.7	7.2	7	2.8	-8.2	18	-
Pop 2	2.6	-28.1	15	2,660	14.4	11	26.7	11.4	17	2.9	-11.3	6	-
Simultaneous selection													
Lines	3.3	-12.9	-	2,443	5.6	-	24.6	3.4	-	3.1	-6.1	-	24
Pop 1	3.2	-10.7	-	2,485	5.5	-	24.0	1.5	-	3.0	-5.2	-	14
Pop 2	3.3	-14.7	-	2,356	4.0	-	25.2	5.6	-	3.2	-5.5	-	10
Overall mean	4.0			2,267			23.7			3.4			

[1]Xs, mean of the selected genotypes; GS, Gain expected from selection; NL, Total number of lines selected (24), separated by population. [2]Pop 1, 'BRS Notável'/'BRS Ametista' population; Pop 2, 'BRS Notável'/CNFC 15872 population.

2013). Based on joint analysis, the mean values of the 114 lines ranged from 2.4 for CNFC 19199 to 5.0 for CNFC 19163 for grain appearance, which were obtained from the 'BRS Notável'/CNFC 15872 and 'BRS Notável'/'BRS Ametista' populations, respectively.

The estimated heritability was moderate (63.1%) (Table 2), indicating the possibility of obtaining genetic gain upon selecting superior lines. Carvalho et al. (2017) obtained a similar heritability estimate (57.5%) upon evaluating progenies. The expected gain upon selecting 24 lines for grain appearance was 10.5%, of which 18 were from the 'BRS Notável'/'BRS Ametista' population (Table 3). Nevertheless, considering the selection in each population, the gain was higher for the 'BRS Notável'/CNFC 15872 population (11.3%), which can be explained by the greater heritability and differential of selection in relation to the other population (Table 2).

In direct selection of the 24 best carioca common bean lines for each trait, the number of lines selected from the 'BRS Notável'/CNFC 15872 population was higher for reaction to fusarium wilt and 100-seed weight (Table 3), while for grain yield, the two populations were equivalent. For grain appearance, the 'BRS Notável'/'BRS Ametista' population had three times the number of lines out of the 24 lines selected, compared with the 'BRS Notável'/CNFC 15872 population.

The gain expected for direct selection per trait showed a possible successful selection; however, breeding programs seek to combine favorable traits in the same genotype (Alvares et al., 2016). Therefore, simultaneous selection was carried out for the four traits, based on the results of joint analysis, which led to gains of 12.9% for reaction to fusarium wilt, 5.6% for grain yield, 3.4% for 100-seed weight, and 6.1% for grain appearance (Table 3). Although gain was lower for each trait in comparison with direct selection, simultaneous selection allowed choosing the lines with greater probabilities of becoming cultivars, since they present phenotypes desirable for more traits in the same line.

Based on simultaneous selection, 14 out of the 24 lines came from the 'BRS Notável'/'BRS Ametista' population. Among the 24 lines selected based on simultaneous selection, CNFC 19126, CNFC 19205, and CNFC 19131 were the most promising, exceeding the 'BRS Notável', the control genotype most resistant to fusarium wilt (Table 4). In addition, these lines should be tested in multiple environments for future recommendation of new cultivars.

The genetic correlation between reaction to fusarium wilt and grain yield was intermediate and negative (r_g= -0.58$^+$), indicating that the greater the resistance

Table 4. Mean adjusted values based on joint analysis of 24 carioca common bean (*Phaseolus vulgaris*) lines from simultaneous selection considering reaction to fusarium wilt, yield, 100-seed weight, and grain appearance (GA) and control genotypes.

Genotype	*Fusarium* wilt (scores from 1 to 9)	Yield (kg ha^{-1})	100-seed weight (g)	GA (scores from 1 to 5)
CNFC 19122[(1)]	2.7	2,394	22.4	2.7
CNFC 19126[(1) (3)]	2.7	2,821	25.1	3.3
CNFC 19235[(2)]	2.7	2,154	28.2	3.4
CNFC 19205[(2) (3)]	2.8	2,543	25.5	2.7
CNFC 19131[(1) (3)]	2.9	2,715	22.6	3.3
CNFC 19174[(1)]	2.9	2,364	23.8	3.0
CNFC 19188[(2)]	3.0	2,204	23.6	3.2
CNFC 19165[(1)]	3.0	2,198	23.7	2.5
BRS Notável	**3.2**	**2,463**	**20.5**	**4.0**
CNFC 19183[(2)]	3.2	2,395	27.7	3.0
CNFC 19133[(1)]	3.3	2,120	25.6	2.9
CNFC 19182[(2)]	3.3	2,304	23.8	2.4
CNFC 19173[(1)]	3.3	2,531	23.9	2.9
CNFC 19156[(1)]	3.4	2,457	24.3	3.0
CNFC 19198[(2)]	3.4	2,772	25.3	3.5
CNFC 19132[(1)]	3.4	2,826	22.9	3.4
CNFC 19228[(2)]	3.5	2,397	23.8	3.4
CNFC 19193[(2)]	3.5	2,269	25.2	3.5
CNFC 19196[(2)]	3.6	2,583	25.6	3.1
CNFC 19144[(1)]	3.7	2,524	23.7	3.0
CNFC 19129[(1)]	3.8	2,342	23.8	3.1
CNFC 19234[(2)]	3.8	2,344	26.2	3.4
CNFC 19130[(1)]	3.8	2,507	23.0	3.0
CNFC 19145[(1)]	3.8	2,498	24.7	3.0
CNFC 19177[(1)]	3.9	2,369	25.5	3.0
CNFC 15872	**4.0**	**2,164**	**23.7**	**2.3**
BRS Ametista	**4.2**	**2,527**	**24.3**	**3.4**
Pérola	**4.6**	**2,099**	**24.5**	**2.9**
BRS Sublime	**5.4**	**1,853**	**21.9**	**2.4**
BRS Estilo	**6.9**	**1,520**	**24.2**	**3.2**
BRS Cometa	**7.7**	**1,149**	**21.0**	**3.4**
Mean of control genotypes	5.2	1,954.4	23.6	3.0
Mean of lines	3.3	2,446.9	24.4	3.1

[(1)]'BRS Notável'/'BRS Ametista' population. [(2)]'BRS Notável'/CNFC 15872 population. [(3)]Most promising lines among the 24 selected.

of the genotype, the greater the grain yield, since the disease causes high yield losses (Pereira et al., 2019). Torres et al. (2022) found higher genetic correlation (-0.93).

The genetic correlation between reaction to fusarium wilt and 100-seed weight was of low magnitude (r_g= -0.36$^+$), which indicates that it is possible to combine resistance to fusarium wilt and grain with greater 100-seed weight, close to that observed by Torres et al. (2022), of -0.28. Between yield and 100-seed weight and between yield and grain appearance, genetic correlation was not significant, indicating an absence of a linear relation between the traits (Ramalho et al., 2012), as observed by Torres et al. (2022) in the presence of fusarium wilt and Nagel et al. (2020) in the absence of the disease.

Conclusions

1. There is a genetic variability among the carioca common bean (*Phaseolus vulgaris*) lines for all the traits evaluated, and the estimates of the genetic parameters show a possible successful selection for reaction to fusarium wilt, grain yield, grain appearance, and 100-seed weight.
2. Twenty-four lines of carioca common bean that were selected combine high resistance to fusarium wilt, grain yield, 100-seed weight, and good grain appearance.
3. CNFC 19126, CNFC 19205, and CNFC 19131 show a better performance than the control genotypes with the highest level of resistance, so their evaluation in multiple environments is recommended, aiming at new resistant cultivars to *Fusarium oxysporum* f. sp. *phaseoli*.

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