Genetics/ Original Article

Selection of carioca common bean lines with slow darkening

Abstract – The objective of this work was to evaluate the interaction between genotypes and environment for seed-coat darkening of common bean (*Phaseolus vulgaris*) seeds, in order to select lines that combine slow darkening, upright plants, resistance to lodging, and higher yield and 100-grain weight, with good adaptability and stability for these traits. Forty-four pre-selected lines, originating from crosses between one cultivar with slow darkening and prostrate plants and four cultivars with normal darkening and upright plants, were evaluated in field trials conducted in 15 environments (combinations of locations, crop seasons, and years). Considering the mean values, adaptability, and stability for each isolated trait, most of the lines presented satisfactory performance: 75% for slow darkening, 48% for high yield, 59% for upright plants, 84% for resistance to lodging, and 68% for 100-grain weight. The effects of environments and of the genotype by environment interaction are important for the five studied traits. The CNFC 16754 and CNFC 16820 lines present slow seed-coat darkening, high yield and 100-grain weight, more upright plant architecture, and greater resistance to lodging, besides high adaptability and stability for these traits, which shows their potential for recommendation as new cultivars and confirms that it is possible to join desirable phenotypes for the five traits evaluated.

Index terms: *Phaseolus vulgaris*, genotype by environment interaction, resistance to lodging, stability, upright architecture.

Seleção de linhagens de feijão carioca com escurecimento lento

Resumo – O objetivo deste trabalho foi avaliar a interação entre genótipos e ambientes para o escurecimento de grãos de feijão carioca (*Phaseolus vulgaris*), a fim de selecionar linhagens que associem escurecimento lento, arquitetura ereta, tolerância ao acamamento, e maior produtividade e peso de 100 grãos, com boa adaptabilidade e estabilidade para esses caracteres. Foram avaliadas 44 linhagens pré-selecionadas, oriundas de cruzamentos entre uma cultivar com escurecimento lento e arquitetura prostrada e quatro cultivares com escurecimento normal e arquitetura ereta, em experimentos de campo conduzidos em 15 ambientes (combinações de locais, épocas de semeadura e anos). Ao se considerar as médias, a adaptabilidade e a estabilidade para cada caráter isoladamente, a maior parte das linhagens apresentou desempenho satisfatório: 75% para escurecimento lento, 48% para alta produtividade, 59% para arquitetura ereta, 84% para tolerância ao acamamento e 68% para peso de 100 grãos. Os efeitos dos ambientes e da interação entre genótipos e ambientes são importantes para os cinco caracteres estudados. As linhagens CNFC 16754 e CNFC 16820 apresentam escurecimento lento dos grãos, alta produtividade e peso de 100 grãos, plantas mais eretas e alta tolerância ao acamamento, além de alta adaptabilidade e estabilidade para esses caracteres, o que mostra o seu potencial para recomendação como novas cultivares e

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confirma que é possível reunir fenótipos desejáveis para os cinco caracteres avaliados.

Termos para indexação: *Phaseolus vulgaris*, interação entre genótipos e ambientes, resistência ao acamamento, estabilidade, arquitetura ereta.

Introduction

Brazil is among the countries that most produce common bean (*Phaseolus vulgaris* L.) (FAO, 2021), with an annual production of around 2,7 million tons (Embrapa, 2021). The "carioca" type – cream-colored seed coat with brown stripes – of common bean is preferred in the country and represents 75% of the market (Pereira et al., 2021).

During the period between grain harvest and sale in the market, high temperature and humidity conditions accelerate the oxidation reaction of the condensed tannins present in the seed coat of the carioca grain, which leads to darkening of the beige tones of the seed coat, lowering the commercial value of the grain (Junk-Knievel et al., 2008; Silva et al., 2008, 2014, 2018; Alvares et al., 2016; Coutin et al., 2017; Erfatpour et al., 2018). Consumers associate dark seed coats in common bean with a low-quality product that is hard to cook (long cooking time) and has a hard shell (high bean firmness).

Junk-Knievel et al. (2008), working with pinto bean, and Silva et al. (2008), with carioca bean, each concluded that seed-coat darkening is under monogenic control, with dominance of the allele that regulates normal darkening. The gene identified by Junk-Knievel et al. (2008) was called *Sd* (slow darkening). After that, Elsadr et al. (2011) reported the presence of two genes controlling seed-coat darkening, with recessive epistasis, with one of the genes (*J*) being responsible for darkening or lack of darkening of the seed coat and the other (*Sd*), for speed of darkening. Alvares et al. (2019) confirmed the monogenic segregation reported by Silva et al. (2008) and found that the gene responsible for darkening in carioca bean and pinto bean may be the same, as shown through the use of a molecular marker. Using an allelism test, Rodrigues et al. (2019) also observed that the *Sd* gene identified in pinto bean is the same one present in carioca bean. In addition, several authors found high heritability estimates (Silva et al., 2014; Alvares et al., 2016), indicating favorable conditions for the selection of lines with slow seed-coat darkening.

In Brazil, a few common bean cultivars show slow seed-coat darkening, but grow into prostrate plants (Alvares et al., 2020). Upright plants are preferable because they create an environment unfavorable to the disease and allow mechanized harvest with less grain loss and with better grain quality (Alvares et al., 2016). However, the cultivars available with upright plant architecture have normal seed-coat darkening. Therefore, combining upright plant architecture and slow seed-coat darkening in the same cultivar would be advantageous. Other desirable phenotypes, such as high yield and larger bean size, are also

important for the good acceptance of a new cultivar (Pereira et al., 2017a; Arns et al., 2018).

Common bean is grown under diverse agroclimatic conditions, and, for this reason, the genotype by environment interaction can affect the selection of superior lines. Under those conditions, analyses of adaptability and stability can assist in identifying promising lines. For grain yield in common bean, several studies have confirmed the importance of the genotype by environment interaction (Alvares et al., 2016; Corrêa et al., 2016; Delfini et al., 2018; Di Prado et al., 2019). However, works of this type are not frequent for seed-coat darkening, 100-grain weight, plant architecture, and resistance to lodging (Alvares et al., 2016; Delfini et al., 2018; Silva et al., 2018).

The objective of this work was to evaluate the interaction between genotypes and environment for seed-coat darkening of common bean seeds, in order to select lines that combine slow darkening, upright plants, resistance to lodging, and higher yield and 100-grain weight, with good adaptability and stability for these traits.

Materials and Methods

The lines used were obtained from Embrapa Arroz e Feijão, located in the municipality of Santo Antônio de Goiás, in the state of Goiás, Brazil. Initially, Silva et al. (2014) obtained segregating populations from crosses between the BRSMG Madrepérola carioca-type cultivar, with slow seed-coat darkening and prostrate plants, and ten cultivars with normal seed-coat darkening and upright plants. These populations were evaluated and the following four were selected to obtain lines: BRSMG Madrepérola × BRS Estilo, BRSMG Madrepérola × BRS Cometa, BRSMG Madrepérola × BRS Notável, and BRSMG Madrepérola × BRS Sublime. The 55 lines obtained from each population were evaluated in three environments for seed-coat darkening, yield, and plant architecture (Alvares et al., 2016, 2019). Based on these results, 11 lines were selected from each of the four populations, totaling 44 lines.

In the present study, these 44 lines and the five parents were evaluated in trials set up in 15 environments in different locations in Brazil: Anápolis, in the state of Goiás; Santo Antônio de Goiás, in the state of Goiás; Brasília, in Distrito Federal; Cáceres, in the state of

Mato Grosso; Belém de São Francisco, in the state of Pernambuco; Carira, in the state of Sergipe; Sete Lagoas, in the state of Minas Gerais; Uberlândia, in the state of Minas Gerais; and Ponta Grossa, in the state of Paraná. Each environment was a combination of location, crop season (rainy, dry, and winter), and year (2012, 2013, and 2014). The trials were conducted in a 7×7 triple lattice design, with plots consisting of two 3 m length rows with a spacing of 0.50 m between rows. Management practices were carried out according to the recommendations for the common bean crop in each region, but without disease control (Melo, 2009). The assessed traits were seed-coat darkening, yield and 100-grain weight, plant architecture, and resistance to lodging.

Plant architecture and resistance to lodging were evaluated according to a scoring scale, ranging from 1 to 9, where 1 refers to phenotypes ideal for mechanized harvest and 9, to phenotypes that cannot be harvested by machines (Melo, 2009). To estimate yield, all the plants of the plot were harvested and threshed; the grains were weighed (kg ha^{-1}) after being dried to 13% moisture. The 100-grain weight was determined by weighing a random sample of 100 beans.

Seed-coat darkening was assessed using the method proposed by Silva et al. (2008) and adapted by Silva et al. (2014), through a scoring scale, ranging from 1 (very light-colored beans) to 5 (dark beans), 90 days after harvest. After harvest, a grain sample from each plot was placed in perforated transparent plastic packaging, and, then, the samples were stored in a shed at ambient temperature and humidity.

Individual and joint analyses of variance were performed for each trait. The homogeneity of residual variances was checked by observing the ratio between the maximum and minimum values of the experimental mean square errors (Pimentel-Gomes, 2000). Means were compared by the Scott-Knott means clustering test, at 10% probability. Selective accuracy was also estimated (Resende & Duarte 2007), a measurement of experimental accuracy not affected by the mean of the environments.

Analyses of stability were also performed for the five traits evaluated, adopting the method of Nunes et al. (2005), also described by Ramalho et al. (2012), using the SAS software (SAS Institute Inc., Cary, NC, USA). The method of Nunes et al. (2005) standardizes the

from 37º42'04" to 57º40'44", and to the different crop seasons (rainy, dry, and winter) and years (2012, 2013, and 2014) of evaluation.

A differentiated response of the genotypes was also detected in the different environments for all traits, due to the genotype by environment interaction (Table 2). Although the interaction for seed-coat darkening has been reported in the literature (Silva et al., 2014; Siqueira et al., 2014; Alvares et al., 2016), only a few environments have been evaluated. However, a larger number of environments is necessary for a more reliable selection of lines. The interaction between genotypes and environment has been frequently reported for yield (Alvares et al., 2016; Corrêa et al., 2016; Delfini et al., 2018; Di Prado et al., 2019), but less for plant architecture, resistance to lodging, and 100-grain weight (Alvares et al., 2016; Delfini et al., 2018; Silva et al., 2018).

When the interaction is significant, an option is to identify the best performing lines in each environment. However, when several traits and environments have to be considered to recommend new cultivars, the most common alternative for most cultures is to identify a few lines with broad adaptability and stability, through stability analyzes (Pereira et al., 2018; Souza et al., 2018). This way, it would be possible to indicate lines as new cultivars that could be used in a greater number of environments.

The cluster analysis for seed-coat darkening allowed classifying the lines in ten groups. Lines CNFC 16709 and CNFC 16871 showed good results, with mean values similar to that of the BRSMG Madrepérola check cultivar (Table 3). The second to the fifth clusters gathered 31 lines, considered to have the slow darkening trait, with mean values ranging from 2.1 to 3.0. The other 11 lines and four cultivars were classified as having normal seed-coat darkening. Therefore, 73% of the lines had bean grains with slow darkening after storage, showing the high efficiency of the selection made by Alvares et al. (2016). The BRS Notável and BRS Cometa cultivars had the darkest grains, with values of 4.8 and 4.9, respectively.

Table 1. Summary of the individual analysis of variance for the evaluation of seed-coat darkening, yield, plant architecture, resistance to lodging, and 100-grain weight of 49 common bean (*Phaseolus vulgaris*) lines, evaluated in 15 environments in the states of Goiás (GO), Sergipe (SE), Pernambuco (PE), Paraná (PR), Minas Gerais (MG), as well as in Distrito Federal (DF), Brazil, in dry, rainy, and winter crop seasons, in 2012, 2013, and 2014.

Environment[1] (location/season/year)	Darkening			Yield (kg ha^{-1})			Architecture			Lodging			100-grain weight (g)		
	Mean	CV[2]	SA[3]	Mean	CV	SA	Mean	CV	SA	Mean	CV	SA	Mean	CV	SA
Brasília 1 in DF/winter/2012	2.9	12.7	0.88	2,866	17.0	0.79	4.7	9.6	0.77	4.5	15.7	0.78	24.0	3.8	0.89
Brasília 2 in DF/winter/2012	3.0	19.3	0.89	2,335	19.9	0.77	4.8	9.7	0.77	4.7	12.7	0.85	27.1	5.3	0.91
SAG in GO/winter/2012	2.9	17.6	0.80	5,303	13.9	0.74	5.2	9.6	0.75	5.2	12.4	0.67	24.4	3.9	0.84
Uberlândia in MG/dry/2013	2.4	12.1	0.90	-	-	-	-	-	-	-	-	-	-	-	-
Anápolis in GO/winter/2013	2.7	17.1	0.93	3,339	206	0.74	4.5	11.2	0.79	4.6	17.8	0.88	25.8	5.5	0.93
Cáceres MT/winter/2013	2.9	15.3	0.94	1,562	17.8	0.79	5.6	10.3	0.81	-	-	-	23.7	5.5	0.94
SAG in GO/winter/2013	3.0	14.5	0.94	-	-	-	-	-	-	-	-	-	-	-	-
Sete Lagoas in MG/winter/2013	2.6	15.7	0.92	4,722	10.9	0.67	-	-	-	-	-	-	22.8	5.1	0.92
Carira in SE/rainy /2013	4.2	9.8	0.93	2,314	13.6	0.80	-	-	-	-	-	-	23.2	3.8	0.92
BSF in PE/rainy/2013	2.8	16.0	0.91	-	-	-	-	-	-	-	-	-	24.7	5.2	0.91
Brasília in DF/rainy/2013	3.0	19.7	0.96	2,342	16.3	0.84	4.9	11.3	0.85	4.5	18.0	0.91	23.1	4.1	0.94
Ponta Grossa in PR/rainy/2013	3.6	15.1	0.96	3,631	14.5	0.89	5.0	8.9	0.86	-	-	-	22.3	5.1	0.95
SAG in GO/rainy /2013	3.4	20.7	0.94	-	-	-	5.7	11.4	0.81	5.2	11.3	0.89	-	-	-
Cáceres in MT/winter/2014	3.1	11.1	0.97	1,934	132	0.90	-	-	-	-	-	-	24.7	4.0	0.95
SAG in GO/winter/2014	3.3	17.3	0.97	2,579	13.7	0.86	5.6	13.8	0.92	5.5	13.6	0.91	22.1	5.7	0.96

[1]SAG, Santo Antônio de Goiás; and BSF, Bélem de São Francisco. [2]Coefficient of variation (%). [3]Selective acuracy.

From the estimates of Z_i for seed-coat darkening, 64% of the lines had good adaptation ($Z_i > 4.0$). The CNFC 16709 and CNFC 16871 lines showed the highest estimates of Z_i (5.2), higher than that found for BRSMG Madrepérola (Table 3). In general, the lines that had the best mean values were the most adapted.

Differences were also observed in the stability of the lines for seed-coat darkening. The stability of approximately 66% of the lines was considered to be good ($CV_i < 15.0\%$). Twelve of these lines had $CV_i \leq 10.0\%$, just as the BRSMG Madrepérola check cultivar (Table 3), showing that, even with environmental variations, their seed coats always have optimal coloring. Considering the mean, adaptability, and stability for seed-coat darkening, 12 lines were identified as superior, most notably CNFC 16871 ($\overline{x} = 1.9$, $Z_i = 5.2$, and $CV_i = 8.8\%$), CNFC 16754 ($\overline{x} = 2.2$, $Z_i = 4.8$, and $CV_i = 9.2\%$), and CNFC 16778 ($\overline{x} = 2.3$, $Z_i = 4.8$, and $CV_i = 8.1\%$).

For grain yield, the cluster analysis formed four groups of mean values. The first group was composed of lines CNFC 16709, CNFC 16757, CNFC 16694, CNFC 16902, and CNFC 16876 and of cultivars BRS Estilo, BRS Notável, BRS Sublime, and BRSMG Madrepérola, with yields ranging from 3,303 to 3,474 kg ha^{-1} (Table 3). The second group consisted of 15 lines, and the third group, of 12 lines and of cultivar BRS Cometa. Another 12 lines had lower yields than BRS Cometa, showing low potential for use as new cultivars.

Twenty lines (45%) had good adaptability estimates for grain yield ($Z_i > 4.0$). Lines CNFC 16709, CNFC 16902, CNFC 16876, CNFC 16757, and CNFC 16694 had an adaptability similar to that of cultivars BRS Estilo, BRS Notável, BRS Sublime, and BRSMG Madrepérola (Table 3). In addition, along with the five check cultivars, 75% of the lines had good stability ($CV_i < 25\%$). Considering the mean, adaptability, and stability for yield, 16 lines were identified as having

Table 2. Summary of the joint analyses of variance for seed-coat darkening, grain yield, plant architecture, resistance to lodging, and 100-grain weight of 49 common bean (*Phaseolus vulgaris*) genotypes evaluated in the states of Goiás, Sergipe, Pernambuco, Paraná, and Minas Gerais, as well as in Distrito Federal, Brazil, in the dry, rainy, and winter crop seasons, in 2012, 2013, and 2014.

Source of variation	Darkening[1]			Yield (kg ha^{-1})			Architecture			Lodging			100-grain weight (g)		
	DF	MS	p	DF	MS	p	DF	MS	p	DF	MS	p	DF	MS	p
Block/locations	30	1.0	-	22	1842297	-	18	1.2	-	14	1.9	-	24	23.5	-
Environment (E)	14	60.5	<0.01	10	198885205	<0.01	8	26.4	<0.01	6	39.4	<0.01	11	617.3	<0.01
Genotypes (G)	48	18.4	<0.01	48	2176829	<0.01	48	4.6	<0.01	48	11.5	<0.01	48	91.0	<0.01
Line (L)	43	7.6	<0.01	43	1898512	<0.01	43	3.3	<0.01	43	8.8	<0.01	43	97.9	<0.01
L/population 1[2]	10	9.3	<0.01	10	2566162	<0.01	10	7.4	<0.01	10	12.1	<0.01	10	114.1	<0.01
L/population 2[3]	10	4.4	<0.01	10	976497	<0.01	10	2.0	<0.01	10	6.0	<0.01	10	100.8	<0.01
L/population 3[4]	10	7.2	<0.01	10	1098064	<0.01	10	1.8	<0.01	10	10.3	<0.01	10	77.4	<0.01
L/population 4[5]	10	6.2	<0.01	10	2798978	<0.01	10	1.9	<0.01	10	5.1	<0.01	10	52.6	<0.01
Contrast	3	19.1	<0.01	3	2413007	<0.01	3	3.5	<0.01	3	13.7	<0.01	3	253.4	<0.01
Parents (P)	4	58.0	<0.01	4	1267377	0.05	4	10.4	<0.01	4	25.0	<0.01	4	25.2	<0.01
L vs P	1	322.0	<0.01	1	17782276	<0.01	1	36.8	<0.01	1	73.2	<0.01	1	59.2	<0.01
G × E	672	0.6	<0.01	480	636521	<0.01	384	0.8	<0.01	288	2.0	<0.01	528	4.3	<0.01
L × E	602	0.6	<0.01	430	611350	<0.01	344	0.7	<0.01	258	2.0	<0.01	473	4.4	<0.01
L/population 1 × E	140	0.6	<0.01	100	528017	<0.01	80	0.7	<0.01	60	1.8	<0.01	110	3.5	<0.01
L/population 2 × E	140	0.5	<0.01	100	431121	<0.01	80	0.6	0.02	60	1.5	<0.01	110	4.0	<0.01
L/population 3 × E	140	0.5	<0.01	100	682532	<0.01	80	0.4	4.69	60	3.2	<0.01	110	3.2	<0.01
L/population 4 × E	140	0.5	<0.01	100	719078	<0.01	80	0.8	<0.01	60	1.3	<0.01	110	5.0	<0.01
Contrast × E	42	1.0	<0.01	30	893530	<0.01	24	1.2	<0.01	18	2.0	<0.01	33	10.6	<0.01
P × E	56	0.4	0.02	40	479709	0.05	32	1.3	<0.01	24	1.9	<0.01	44	3.0	<0.01
(L vs P) × E	14	1.5	<0.01	10	2346121	<0.01	8	3.7	<0.01	6	4.1	<0.01	11	3.9	0.16
Error	1,440	0.2	-	1,056	248557	-	864	0.3	-	672	0.6	-	1,152	1.4	-

[1]DF, degrees of freedom; MS, mean square; and p, probability (%). [2]'BRSMG Madrepérola' × 'BRS Sublime'. [3]'BRSMG Madrepérola' × 'BRS Cometa'. [4]'BRSMG Madrepérola' × 'BRS Estilo'. [5]'BRSMG Madrepérola' × 'BRS Notável'.

Table 3. Estimates of mean values and of adaptability (Z_i) and stability (CV_i) parameters, obtained by the method of Nunes et al. (2005), for seed-coat darkening, yield, plant architecture, resistance to lodging, and 100-grain weight of 49 lines and five check cultivars of common bean (*Phaseolus vulgaris*), evaluated in different environments in the states of Goiás, Sergipe, Pernambuco, Paraná, and Minas Gerais, as well as in Distrito Federal, Brazil, in the dry, rainy, and winter crop seasons, in 2012, 2013, and 2014.

Line or cultivar	Darkening			Yield (kg ha⁻¹)			Architecture			Lodging			100-grain weight (g)		
	$X^{(1)}$	$Z_i^{(2)}$	$CV_i^{(3)}$	$X^{(1)}$	Z_i	CV_i	$X^{(1)}$	Z_i	CV_i	$X^{(1)}$	$Z_i^{(2)}$	$CV_i^{(3)}$	$X^{(1)}$	Z_i	CV_i
CNFC 16871	1.9a	5.2	8.8	3,041b	4.2	35.6	4.9b	4.1	12.9	4.9d	3.9	18.7	23.0e	3.8	17.9
CNFC 16709	1.9a	5.2	11.2	3,474a	4.9	15.2	5.1c	3.8	26.1	5.2d	4.2	24.8	23.8d	4.1	12.4
BRSMG Madrepérola	2.1a	5.0	10.0	3,303a	4.5	17.4	5.6d	3.1	26.8	6.2f	2.7	16.9	24.0d	4.2	12.7
CNFC 16697	2.1b	4.9	12.6	3,161b	4.4	14.3	5.9e	2.5	33.4	5.9f	3.1	23.5	25.5b	5.3	16.2
CNFC 16754	2.2b	4.8	9.2	3,140b	4.4	18.2	5.1c	3.8	15.3	5.2d	3.9	10.5	24.0d	4.2	9.1
CNFC 16778	2.3b	4.8	8.1	3,027b	4.2	26.6	5.2c	3.7	12.8	5.8f	3.3	9.6	23.3e	3.7	11.7
CNFC 16772	2.3c	4.7	15.6	3,115b	4.3	24.1	5.2c	3.7	26.2	6.8h	3.3	18.7	23.1e	3.7	22.3
CNFC 16757	2.3c	4.6	21.0	3,289a	4.6	13.4	5.2c	3.7	14.6	5.4e	3.4	31.9	23.2e	3.8	13.9
CNFC 16729	2.4c	4.6	10.2	2,898c	3.8	17.4	5.5d	3.2	22.6	5.9f	2.8	16.8	24.7c	4.7	12.0
CNFC 16866	2.4c	4.6	11.4	2,982c	4.0	20.5	5.1c	3.9	14.5	5.2d	3.8	11.7	22.7f	3.8	14.3
CNFC 16763	2.4c	4.6	8.3	2,698d	3.4	23.2	5.0c	3.9	11.6	5.0d	3.7	18.7	21.2h	2.9	20.1
CNFC 16726	2.4c	4.6	13.2	2,649d	3.3	22.3	4.7b	4.4	13.3	4.1b	4.7	12.0	20.7i	2.5	24.8
CNFC 16838	2.5c	4.5	9.7	2,927c	3.8	17.3	5.1c	3.9	30.3	5.7f	3.4	16.3	23.8d	4.2	13.9
CNFC 16702	2.5d	4.4	10.2	3,025b	4.1	18.1	5.5d	3.2	33.7	5.5e	3.8	21.5	21.1h	2.8	20.1
CNFC 16775	2.5d	4.4	9.4	3,100b	4.2	22.2	5.5d	3.1	21.9	5.4e	3.7	18.8	23.2e	3.9	14.3
CNFC 16690	2.5d	4.4	16.4	2,953c	3.7	27.2	4.9b	4.1	24.0	5.0d	3.9	24.4	22.0g	3.2	14.9
CNFC 16747	2.5d	4.4	12.4	2,820c	3.7	25.6	4.8b	4.3	18.3	3.9a	5.2	11.3	21.8g	3.3	14.0
CNFC 16857	2.5d	4.4	10.0	2,688d	3.4	38.2	4.7b	4.5	20.9	4.3b	4.7	15.4	23.1e	3.7	16.6
CNFC 16694	2.6d	4.3	9.7	3,272a	4.5	23.6	4.7b	4.5	14.0	4.2b	4.8	12.1	21.9g	3.2	13.9
CNFC 16741	2.6d	4.4	6.6	3,020b	4.2	27.6	5.2c	3.7	14.1	5.5e	3.5	20.2	23.4e	3.9	13.3
CNFC 16902	2.6d	4.3	11.8	3,409a	4.9	23.0	5.3c	3.5	16.0	5.6e	3.4	11.7	24.6c	4.8	18.9
CNFC 16761	2.6d	4.4	11.6	2,756d	3.5	22.5	4.6b	4.7	13.0	4.7c	4.3	19.0	20.6i	2.6	23.2
CNFC 16831	2.6d	4.3	14.0	2,769d	3.5	8.3	4.3a	5.3	12.8	3.5a	5.4	12.2	25.3b	5.0	7.0
CNFC 16872	2.6d	4.3	9.1	3,222b	4.5	20.6	5.5d	3.1	24.4	5.4e	3.5	19.6	24.0d	4.5	15.6
CNFC 16788	2.6d	4.3	9.5	3,153b	4.4	20.0	5.4d	3.3	19.4	5.4e	3.7	22.7	23.0e	3.8	16.1
CNFC 16713	2.6d	4.3	8.2	2,596d	3.2	27.8	4.4a	4.9	13.7	4.2b	5.1	10.8	20.8i	2.5	21.6
CNFC 16820	2.8e	4.1	12.1	2,932c	3.9	21.5	4.7b	4.4	11.5	4.8d	4.5	14.8	22.9e	3.6	12.9
CNFC 16843	2.8e	4.1	12.0	2,805c	3.6	20.2	5.2c	3.6	22.8	5.2d	3.9	31.8	22.2f	3.4	19.0
CNFC 16862	2.8e	4.1	12.6	3,220b	4.5	12.1	4.9b	4.2	23.0	5.0d	3.9	21.3	21.3h	3.0	24.4
CNFC 16724	2.8e	4.0	17.7	3,102b	4.1	20.5	4.5a	4.8	17.1	4.7c	4.4	14.0	21.8g	3.0	14.2
CNFC 16881	2.8e	4.0	18.5	2,723d	3.5	24.7	5.4c	3.6	26.9	5.9f	3.2	25.0	23.3e	4.0	11.5
CNFC 16827	2.9e	4.0	11.4	2,602d	3.2	21.5	5.1c	3.8	13.6	5.6e	3.5	22.6	22.5f	3.4	16.0
CNFC 16876	2.9e	3.8	10.1	3,305a	4.7	17.3	5.3c	3.5	27.9	5.2d	3.7	15.5	23.5e	4.1	17.6
CNFC 16877	3.0e	3.8	18.2	2,898c	3.8	16.5	4.9b	4.2	13.4	5.5e	3.5	11.2	24.4c	4.5	11.3
CNFC 16692	3.1f	3.6	16.8	2,646d	3.2	34.7	5.8e	2.6	31.5	6.4g	2.3	26.6	22.3f	3.3	14.7
CNFC 16826	3.1f	3.6	13.6	2,590d	3.2	23.5	4.9b	4.1	16.5	5.1d	4.3	11.0	23.1e	3.7	19.1
CNFC 16793	3.1f	3.7	17.4	2,943c	3.9	17.3	5c	4.1	13.4	5.0d	4.3	17.9	26.0a	5.3	11.5
CNFC 16852	3.1f	3.6	14.2	2,448d	2.8	28.1	5.1c	3.9	23.2	5.9f	3.0	15.4	23.5e	3.9	20.8
CNFC 16832	3.2f	3.5	17.5	2,847c	3.7	22.7	4.9b	4.3	18.1	4.4b	4.6	18.0	26.2a	5.4	11.8
CNFC 16849	3.2f	3.5	18.7	2,986c	3.9	24.9	4.8b	4.3	17.0	4.9d	4.1	10.4	25.9a	5.2	12.3
CNFC 16830	3.2f	3.5	21.5	2,886c	3.8	26.0	5.1c	3.7	26.8	4.8d	4.3	14.3	25.7b	5.2	13.6
CNFC 16819	3.3g	3.4	16.7	2,710d	3.4	15.0	4.6b	4.5	14.4	4.7c	4.4	20.8	24.0d	4.2	14.8
CNFC 16846	3.4g	3.3	19.8	3,193b	4.3	19.1	4.9b	4.2	13.8	5.0d	4.2	16.9	26.4a	5.6	8.7
CNFC 16722	3.6h	3.0	28.4	3,136b	4.2	21.6	4.9b	4.0	21.3	4.8d	4.0	22.7	24.0d	4.1	14.4
CNFC 16760	3.7h	2.9	17.6	3,006b	4.1	34.9	5.2c	3.6	15.7	5.4e	3.6	12.9	26.3a	5.5	10.3
BRS Sublime	4.1i	2.4	17.7	3,337a	4.8	16.0	4.3a	5.1	24.1	3.8a	5.3	13.7	24.2c	4.4	14.2
BRS Estilo	4.1i	2.4	25.1	3,499a	5.0	9.3	4.2a	5.2	20.7	3.9a	5.1	19.8	25.5b	5.0	8.4
BRS Notável	4.8j	1.5	42.4	3,403a	4.9	22.0	4.2a	5.3	23.4	3.7a	5.5	17.4	23.7d	4.2	12.4
BRS Cometa	4.9j	1.4	49.6	2,980c	4.0	16.3	4.3a	5.1	17.2	3.7a	5.2	13.2	23.0e	3.7	15.2

[1]Means followed by equal letters do not differ by the test of Scott-Knott, at 10% probability. [2]Parameter of adaptability by the method of Nunes et al. (2005). [3]Coefficient of variation of the variable standardized for each genotype, considered the parameter of stability by the method of Nunes et al. (2005).

mean values higher than 3,025 kg ha^{-1}, Z_i greater than 4, and CV_i lower than 25%; CNFC 16709, CNFC 16757, CNFC 16876, CNFC 16902, and CNFC 16694 stood out.

Five groups of means were formed for plant architecture. The first was composed of cultivars BRS Estilo, BRS Notável, BRS Cometa, and BRS Sublime (Table 3), which clearly have upright plants (Alvares et al., 2016; Silva et al., 2018), and of lines CNFC 16831, CNFC 16713, and CNFC 16724; these lines had scores from 4.2 to 4.5 and were the most upright plants. The second and third groups consisted of 16 and 18 lines, respectively, which did not have an ideal plant architecture, but showed more upright than BRSMG Madrepérola, classified in the fourth group of mean values, with scores from 5.4 to 5.6. Therefore, 84% of the lines were more upright than BRSMG Madrepérola, confirming once more the effectiveness of the selection made by Alvares et al. (2016) and that it is also possible to obtain lines with more upright plants. Furthermore, in terms of plant architecture, 19 lines (43%) had good adaptability ($Z_i > 4.0$). Line CNFC 16831 had better adaptability ($Z_i = 5.3$), together with cultivars BRS Notável, BRS Estilo, BRS Cometa, and BRS Sublime. Moreover, 61% of the lines had good stability ($CV_i < 20\%$). Among the 15 lines that showed the best means, adaptability, and stability for upright plant architecture the most noteworthy were CNFC 16831, CNFC 16713, and CNFC 16724.

Resistance to lodging was greater in 82% of the lines, compared with cultivar BRSMG Madrepérola (Table 3). CNFC 16831 and CNFC 16747 stood out for having a performance similar to that of the check cultivars with lower lodging, i.e., BRS Cometa, BRS Notável, BRS Sublime, and BRS Estilo. Seventeen lines (39%) had good adaptability, and, among them, the same two lines stood out again. In addition, 68% of the lines had good stability ($CV_i < 20\%$). Twenty-one lines combined good mean values, high adaptability, and high stability for resistance to lodging, and the most noteworthy were CNFC 16831, CNFC 16747, and CNFC 16726.

For 100-grain weight, CNFC 16846, CNFC 16760, CNFC 16832, CNFC 16793, and CNFC 16849 were in the group with the highest mean values, from 25.9 to 26.4 g, which were considered even superior to those of the check cultivars (Table 3) (Pereira et al., 2017a; Arns et al., 2018). The second group consisted of another

three lines, together with cultivar BRS Estilo, with mean values ranging from 25.3 to 25.7. The third group was composed of the BRS Sublime cultivar, together with three other lines, with mean values ranging from 24.2 to 24.7. Cultivars BRS Estilo and BRS Sublime are standards in the market as they have an 100-grain weight higher than 24 g. Therefore, 25% of the lines have an optimal-sized bean grain.

Eighteen lines (41%) showed an adaptability higher than the mean for 100-grain weight. Eight lines had high adaptability, with Z_i estimates greater than or equal to that of BRS Estilo (Table 3). Twenty-six lines (59%) presented estimates of CV_i lower than 15%, indicating high stability. Eleven lines combined high means, adaptability, and stability for 100-grain weight, with CNFC 16760, CNFC 16832, and CNFC 16793 being highlighted.

The identification of promising common bean lines to obtain new cultivars is a huge challenge, since lines must combine various phenotypes of agronomic interest and with grain quality, so that they have potential of becoming cultivars. Superiority for one or even a few traits is not enough. In the common bean production chain, the consumer is more and more demanding in regard to product quality, and the producer aims at greater profit from production (Pereira et al., 2017b). Therefore, it is necessary to select lines that combine desirable phenotypes in relation to the commercial quality of the grain, such as slow seed-coat darkening and 100-grain weight, as well as agronomic quality, including high yield, upright plants, and resistance to lodging. Besides traits of interest for the market, lines must show stability and be adapted to various environments. A wide adaptation favors a greater use of the cultivars in different regions and growing conditions, which is interesting for Brazil, where the public sector is the main responsible for supplying the market due to the low use of certified seeds.

The results of selection for each isolated trait show a large number of lines that have good mean values, high adaptability, and high stability for each trait: 27 lines (61%) for slow seed-coat darkening, 16 lines (37%) for high yield, 15 lines (34%) for upright plants, 20 lines (45%) for resistance to lodging, and 14 lines (32%) for high 100-grain weight. However, the number of lines with desirable phenotypes for the traits simultaneously is much smaller, which was expected and has been reported in other studies (Alvares et al., 2016; Silva et al., 2018; Di Prado et al., 2019).

Considering simultaneous selection for the five evaluated traits, eight lines were identified as superior, originating from four populations (crosses between the cultivars in parentheses): CNFC 16694 and CNFC 16709 (BRSMG Madrepérola x BRS Sublime); CNFC 16754 (BRSMG Madrepérola x BRS Estilo); CNFC 16820 and CNFC 16843 (BRSMG Madrepérola x BRS Cometa); and CNFC 16862, CNFC 16866, and CNFC 16876 (BRSMG Madrepérola x BRS Notável) (Table 3). Among these eight lines, CNFC 16754 and CNFC 16820 stood out (Figure 1), showing the greatest potential to be recommended as new cultivars with slow seed-coat darkening and more upright plants. However, these lines should be evaluated in trials in multiple environments to verify their true potential for recommendation as new cultivars.
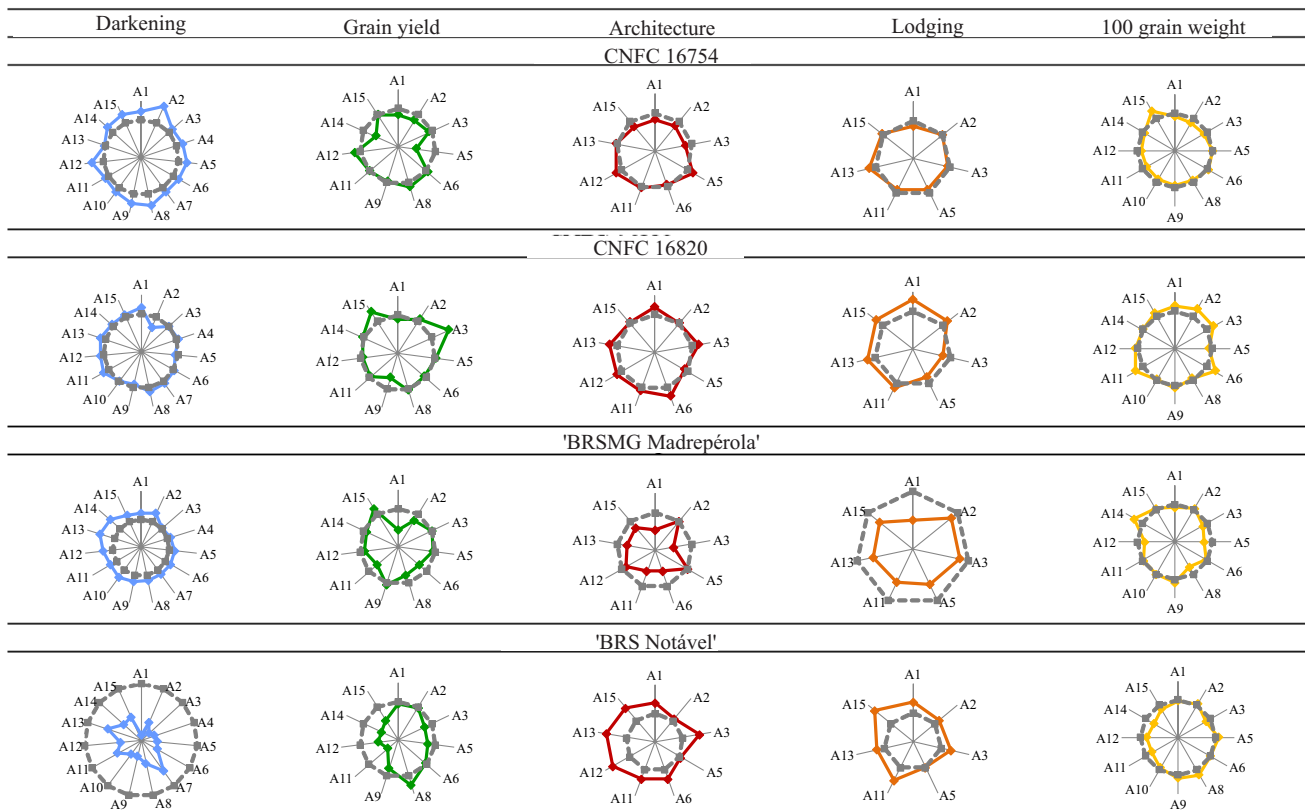

Figure 1. Graph representation of the performance of lines, with the best mean values for seed-coat darkening, yield (kg ha^{-1}), plant architecture, lodging, and 100-grain weight (g), and of two check cultivars of common bean (*Phaseolus vulgaris*), using the graph method of Nunes et al. (2005). The value of the constant associated with variable Z_i equal to 4, represented by the lines in gray, and the axis refer to the different environments evaluated in Brazil: A1, Brasília, in Distrito Federal, in the winter crop season of 2012; A2, Brasília, in Distrito Federal, in the winter crop season of 2012; A3, Santo Antônio de Goiás, in the state of Goiás, in the winter crop season of 2012; A4, Uberlândia, in the state of Minas Gerais, in the dry crop season of 2013; A5, Anápolis, in the state of Goiás, in the winter crop season of 2013; A6, Cáceres, in the state of Mato Grosso, in the winter crop season of 2013; A7, Santo Antônio de Goiás, in the state of Goiás, in the winter crop season of 2013; A8, Sete Lagoas, in the state of Minas Gerais, in the winter crop season of 2013; A9, Carira, in the state of Sergipe, in the rainy crop season of 2013; A10, Belém de São Francisco, in the state of Pernambuco, in the rainy crop season of 2013; A11, Brasília, in Distrito Federal, in the rainy crop season of 2013; A12, Ponta Grossa, in the state of Paraná, in the rainy crop season of 2013; A13, Santo Antônio de Goiás, in the state of Goiás, in the rainy crop season of 2013; A14, Cáceres, in the state of Mato Grosso, in the winter crop season of 2014; and A15, Santo Antônio de Goiás, in the state of Goiás, in the winter crop season of 2014.

Conclusions

1. Genotype by environment interaction is important for seed-coat darkening, yield, 100-grain weight, plant architecture, and resistance to lodging of common bean (*Phaseolus vulgaris*).

2. Lines CNFC 16754 and CNFC 16820 present slow seed-coat darkening, high yield and 100-grain weight, more upright plant architecture, and greater resistance to lodging, as well as high adaptability and stability for these traits in different combinations of locations, crop seasons, and years, showing their potential for recommendation as new cultivars and confirming that it is possible to join desirable phenotypes for the five studied traits.

Acknowledgments

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