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Scientific Article
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Selection of new common bean lines for high grain quality and mineral concentration[1]

Seleção de novas linhagens de feijão para alta qualidade de grãos e concentração de minerais

Nerinéia Dalfollo Ribeiro[2]*, Greice Godoy dos Santos[2], Greice Rosana Kläsener[2], Fabricio Fuzzer de Andrade[2], Henrique da Silva Argenta[2]

ABSTRACT - The development of new common bean lines with traits that meet consumer preference increases their probability of use as food. The objectives of this work were to evaluate the genetic variability of common bean lines and cultivars for grain quality traits and mineral concentration and to select superior lines using the rank-sum index with differentiated economic weights. The experiments were carried out in two growing seasons to evaluate 17 common bean genotypes. The ten grain quality traits and the concentration of seven minerals were determined in raw grains. A significant effect for genotype was observed for 15 traits and a significant genotype x environment interaction was found for 14 traits. High heritability (≥ 60.00%) and genetic gain estimates favorable to the objectives of selection of superior light-and dark-grain common bean lines for most of grain quality traits and mineral concentration were obtained. The common bean lines and cultivars show genetic variability for all grain quality traits and mineral concentration, except for copper concentration. Four carioca (LEC 04-16, Linhagem 110, UEM 266 and Pérola) and four black (TB 17-03, SM 1510, BRS Intrépido and Fepagro Triunfo) common bean genotypes are superior for several grain quality traits and have high concentrations of potassium, phosphorus, calcium and iron, showing potential for use in breeding and nutrition.

Key words: *Phaseolus vulgaris* L. Genotype x environment interaction. Rank-sum index. Differentiated economic weights.

RESUMO - O desenvolvimento de novas linhagens de feijão com caracteres que atendam a preferência dos consumidores aumenta a sua probabilidade de uso na alimentação. Os objetivos desse trabalho foram avaliar a variabilidade genética de linhagens e cultivares de feijão para caracteres da qualidade de grãos e concentração de minerais e selecionar as linhagens superiores usando o índice de soma de ranks com pesos econômicos diferenciados. Os experimentos foram conduzidos em duas épocas de cultivo para avaliar 17 genótipos de feijão. Os dez caracteres da qualidade de grãos e a concentração de sete minerais foram determinados em grãos crus. Efeito significativo para genótipo foi observado para 15 caracteres e interação genótipo x ambiente significativa foi constatada para 14 caracteres. Alta herdabilidade (≥ 60,00%) e estimativas de ganho genético favoráveis aos objetivos da seleção de linhagens de feijão de grãos claros e escuros superiores para a maioria dos caracteres da qualidade de grãos e concentração de minerais foram obtidas. As linhagens e cultivares de feijão apresentam variabilidade genética para todos os caracteres da qualidade de grãos e concentração de minerais, exceto para a concentração de cobre. Quatro genótipos de feijão carioca (LEC 04-16, Linhagem 110, UEM 266 e Pérola) e quatro genótipos de feijão preto (TB 17-03, SM 1510, BRS Intrépido e Fepagro Triunfo) são superiores para vários caracteres da qualidade de grãos e possuem alta concentração de potássio, fósforo, cálcio e ferro, evidenciando potencial de uso no melhoramento e na nutrição.

Palavras-chave: *Phaseolus vulgaris* L. Interação genótipo x ambiente. Índice de soma de ranks. Pesos econômicos diferenciados.

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*Author for correspondence
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[1]This work was carried out with financial support from National Council for Scientific and Technological and Development (CNPq)
[2]Departament of Plant Science, Rural Sciences Center, Universidade Federal de Santa Maria, Santa Maria-RS, Brazil, nerineia@hotmail.com (ORCID ID 0000-0002-5539-0160), godoy.greice@gmail.com (ORCID ID 0000-0002-9104-0379), rosanaklasener@hotmail.com (ORCID ID 0000-0002-3957-0364), fabriciofuzzer@yahoo.com (ORCID ID 0000-0003-3383-0038), henriqueargenta@hotmail.com (ORCID ID 0000-0001-5464-6382)

INTRODUCTION

Great genetic variability for the quality of common bean grains (*Phaseolus vulgaris* L.) has been described in the literature (HERRERA-HERNÁNDEZ *et al*., 2018; PERINA *et al*., 2014; RIVERA *et al*., 2016; SILVA *et al*., 2016). This allows breeding programs to develop new common bean lines of different grain types, with varying colors, sizes and requiring less time to cook, thereby meeting the preference of several consumers. According to Gathu and Njage (2012), the color and size of grains are the two most relevant traits evaluated by consumers when they buy common beans. More recently, cooking time has become more important when choosing common beans, as many people have started to prepare their meals at home during the coronavirus pandemic.

Beans are important sources of protein, carbohydrates, dietary fiber, vitamins and minerals that confer several protective health effects (SUÁREZ-MARTÍNEZ *et al*., 2016). Potassium and magnesium could reduce cases of hypertension (BARBAGALLO; VERONESE; DOMINGUEZ, 2021; MCDONOUGH; YOUN, 2017), phosphorus and calcium act in protection fractures (LI *et al*., 2018; SERNA; BERGWITZ, 2020), iron and copper in prevention of anemia (DEV; BABITT, 2017; WAZIR; GHOBRIAL, 2017) and zinc is being considered as prophylactic or adjunct therapy for covid-19 (JOACHIMIAK, 2021).

Mineral concentration has been widely evaluated in common bean genotypes and expressive genetic variability has been reported (DELFINI *et al*., 2020; JAN *et al*., 2021; MCCLEAN *et al*., 2017; YEKEN *et al*., 2019). This is favorable to the development of new biofortified common bean lines, especially with the grain types most produced in Brazil, namely, carioca (beige seed coat with brown streaks), black and cranberry (cream seed coat with red streaks) beans. However, grain quality traits and mineral concentration are affected by the genotype x environment interaction (DIAS *et al*., 2021; RIBEIRO *et al*., 2021; RIBEIRO; KLÄSENER, 2020; STECKLING *et al*., 2017). This requires that the selection of new common bean lines with grain traits most appreciated by consumers should consider data obtained in a greater number of environments.

The simultaneous selection for several grain quality traits and mineral concentration is an important strategy to be implemented in the routine of common-bean breeding programs. The use of selection indices has enabled the selection of superior common bean lines for most grain quality traits and/or mineral concentration (ARNS *et al*., 2018; DIAS *et al*., 2021; RIBEIRO *et al*., 2021; RIBEIRO; KLÄSENER, 2020; SILVA *et al*., 2018). However, none of these works considered in the selection, the most relevant criteria, that determine consumers' choice of common bean cultivar. If different economic weights are assigned to the grain quality traits and mineral concentration, based on the order of consumer preference, this will result in greater efficiency in the selection of superior common bean lines. This is unprecedented and may increase the probability of acceptance of a new common bean cultivar in the diet, representing marketing advantages for breeding programs. Therefore, the objectives of this study were to evaluate the genetic variability of common bean lines and cultivars for grain quality traits and mineral concentration and to select superior lines using a selection index and differentiated economic weights that represent the order of preference of consumers for the grain traits.

MATERIAL AND METHODS

Description of experiments

The experiments were installed in 2019 in the two recommended seasons for common bean cultivation in Rio Grande do Sul (RS), dry and rainy seasons, corresponding to sowing in summer and late winter, respectively. The two experiments were carried out at the Federal University of Santa Maria, Santa Maria, RS, Brazil, located at the following geographic coordinates: latitude 29º42´S, longitude 53º49´W and 95 m altitude. The region's climate is humid subtropical with hot summers and no clearly defined dry season.

The soil is a typic alitic Argisol, Hapludalf, and was prepared in a conventional way, with two plows and one harrow. Soil analysis revealed the following chemical composition: pH (H_2O) of 5.9; 19.0 g kg^{-1} organic matter; 24.5 mg dm^{-3} P; 44.0 mg dm^{-3} K; 6.8 cmol dm^{-3} Ca; 2.5 cmol dm^{-3} Mg; 517.8 mg dm^{-3} Fe; and 0.8 mg dm^{-3} Zn. The application of the following fertilizer was required at sowing: 160 kg ha^{-1} of the 05-20-20 formula (urea: 45% nitrogen, single superphosphate: 18% P_2O_5 and potassium chloride: 60% K_2O).

A randomized blocks experimental design with three replicates was used. The experimental unit was formed by four lines 4 m long, spaced 0.5 m apart. The useful area consisted of the two central lines (4 m^2), in order to avoid mixing genotypes. A total of 18 common bean genotypes (lines and cultivars) of different grain types were evaluated: black (CHP 04-239-01, TB 17-02, CHP 01-182-12, BRS Intrépido, LP 13-624, SM 1510, TB 17-03 and Fepagro Triunfo); pink (CNFRS 15558); cranberry (CNFRJ 15411); and carioca (Fepagro Garapiá, Linhagem 110, FAP-F3-2 SEL, Pérola, LEC 04-16, UEM 266, LP 13-84 and SM 05 11). The cultivars BRS Intrépido, Fepagro Triunfo, Fepagro Garapiá and Pérola are registered for cultivation in RS, therefore they were considered controls. These cultivars and lines were developed by public research institutions that participated of the Value for Cultivation and Use (VCU) experiment of the Southern Brazilian common bean network of the 2018 and 2019 biennium and are representative of the most produced Mesoamerican and Andean grains in Brazil. The line SM 05 11 was not evaluated in the 2019 rainy season, as there was little availability of seeds.

Management practices were uniform and homogeneous and consisted of: (1) seed treatment with the fungicide Maxim® (Fludioxonil and Metalaxyl-M) and the insecticide Cruiser® 350 FS (Thiamethoxam) at a dose of 200 mL 100 kg^{-1} of seeds; (2) application of the pre-emergent herbicide Dual Gold® (S-Metolachlor) at a dose of 1.25 L ha^{-1}; (3) mechanically eliminating weed plants; (4) insect control using Engeo™Pleno (Thiamethoxam and Lambda-cyhalothrin) at a dose of 125 mL ha^{-1}; (5) topdressing with 40 kg ha^{-1} of urea (45% nitrogen) at the first open trifoliate leaf stage (V3); and (6) irrigation to ensure plant stand uniformity.

The experiments were harvested manually at the plant maturation stage (R9). The harvested plants were identified and placed in a greenhouse until it was possible to thresh the grains. After processing, the grains were kept under refrigeration (temperature of 5 ºC and relative humidity of 75%) until the moment of analysis.

Evaluation of grain quality and mineral concentration

Grain quality was evaluated by color (L*, a* and b* values), mass of 100 grains, grain dimensions (length, width and thickness) and by cooking (absorption, normal grains and cooking time). The color of the grains was determined in a portable colorimeter, using the L* a* b* scale. The L* value represents the luminosity and varies from black to white (BERNARDO, 2010), with the highest values being related to the greater lightness of the grains. The a* value quantifies the variation between green and red, so higher values are associated with more reddish grains. The b* value measures the variation between blue and yellow, so the higher this value, the more yellowish the grain. The mass of 100 grains was obtained with moisture standardized at 13% by weighing 100 grains on a precision balance. The color and mass of 100 grains analyses were performed on three samples of grains collected randomly in each replicate.

Grain dimensions were determined on 10 randomly sampled grains in each replicate, using a digital caliper. The length was measured parallel to the hilum, the width was quantified from the hilum to the opposite side, and the thickness was obtained perpendicular to the length and width. Cooking was evaluated using a sample of 25 grains/replicate which was soaked in 50 mL of distilled water for 8 h at room temperature (20 ± 2 °C). The water was removed and the grains were superficially dried with a paper towel. Absorption was calculated as the difference in grain weight after and before soaking and expressed in %. The grains that absorbed water were counted and presented in % to characterize the normal grains. Cooking time was quantified in a 25-plunger Mattson cooker, similar to that described by Ribeiro *et al*. (2021).

The concentration of seven minerals (potassium, phosphorus, calcium, magnesium, iron, zinc and copper) was analyzed in samples of 30 g of grains/replicate. The grains were ground to obtain a fine and homogeneous raw common bean flour. A 0.5 g aliquot of this sample was used for the acid digestion process. The amounts of nitric and perchloric acids used and the cold and hot digestion times used followed the methodology described by Miyazawa *et al*. (2009). The concentration of all minerals was obtained using an atomic absorption spectrophotometer, except potassium, which was determined in a flame photometer, and phosphorus, which was quantified in an optical emission spectrophotometer.

Statistical analyses

The data obtained were submitted to individual analysis of variance and the homogeneity of residual variances was verified by Hartley's maximum F test. The combined analysis of variance was performed with the common genotypes evaluated in the two experiments. For traits expressed in percentage (absorption and normal grains) the following transformation was applied:

$$\sqrt{\chi + 0.5} \quad (1)$$

in which χ is the trait value.

The effects of genotype (G), environment (A) and G x A interaction were considered fixed and the level of significance was evaluated by the F test, at 5% probability. The grouping of means was carried out using the Scott-Knott test, at 5% probability.

The rank-sum index (MULAMBA; MOCK, 1978) was applied to select the superior common bean cultivars for grain quality traits and mineral concentration. In this analysis, broad sense heritability and selection gain estimates were also obtained. The following economic weights were used considering the most important traits that determine consumers' choice of common bean cultivar: 10 for the L* value, 4 for the mass of 100 grains, 3 for the cooking time, 2 for the mineral concentration and 1 for the other traits. In order to select the four superior light-grain common bean lines (carioca, pink and/or cranberry) inverse selection was applied for the a* and b* values and cooking time and direct selection was carried out for the other traits. In order to select the four superior dark-grain common bean lines inverse selection was used for values of L*, a* and b* values and cooking time and direct selection was employed for the other traits. All statistical analyses were performed using the Genes program (CRUZ, 2016).

RESULTS AND DISCUSSION

Genetic variability for grain quality traits and mineral concentration

Homogeneous residual variances were obtained for all traits in the two growing seasons and this allowed the combined analysis of variance to be performed for the 17 traits. A significant effect for genotype was observed for 15 of the 17 traits evaluated (Table 1), showing that there is genetic variability between common bean lines and cultivars for most of the grain quality traits and mineral concentration. Previous works also found expressive variation for the grain quality traits (HERRERA-HERNÁNDEZ *et al*., 2018; PERINA *et al*., 2014; RIVERA *et al*., 2016; SILVA *et al*., 2016) and mineral concentration (DELFINI *et al*., 2020; JAN *et al*., 2021; MCCLEAN *et al*., 2017; YEKEN *et al*., 2019) in common bean genotypes, which allows the selection of superior lines. For zinc and copper concentrations did not found a significant effect for genotype in the present study and by Maziero *et al*. (2015) for copper concentration evaluated in common bean lines. We hypothesize that common bean lines evaluated in the VCU experiment of the Southern Brazilian network of the 2018 and 2019 biennium were not biofortified for zinc and copper. However, zinc concentrations in common bean genotypes changed with the growing environment, i.e, a significant genotype x environment interaction was obtained for this mineral. The observed differences can be attributed to climatic factors (temperature, precipitation, solar radiation, among others) and biotic factors (diseases, pests and weeds).

Fourteen of the 17 evaluated traits showed a significant genotype x environment interaction, indicating that the grain quality traits and mineral concentration of common bean genotypes vary with the growing environment, confirming the results described by Dias *et al.* (2021), Ribeiro and Kläsener (2020), Ribeiro *et al.* (2021) and Steckling *et al.* (2017). Therefore, common bean lines must be evaluated in different growing environments so that selection for high grain quality and mineral concentration is carried out successfully.

Coefficient of experimental variation values ≤ 16.10% were obtained for all traits (Table 1), indicating high experimental precision, according to the classes established by Pimentel Gomes (1985). Selective accuracy also revealed that the traits were evaluated with high experimental precision (≥ 0.77), except for the zinc and copper concentrations that exhibited low experimental precision (≤ 0.32), according to the classes proposed by Resende and Alves (2020). The magnitude of the statistics analyzed in the present study indicates a low experimental error in the determination of most of the evaluated traits and this is favorable to the selection of superior common bean lines for the grain quality traits and mineral concentration.

Table 1 - Combined analysis of variance containing the degrees of freedom (DF), mean squares, mean, coefficient of experimental variation (CEV) and selective accuracy (SA) for the traits of L* value (L*), a* value (a*), b* value (b*), mass of 100 grains (M100G, g), grain length (Length, mm), grain width (Width, mm), grain thickness (Thickness, mm), absorption (Abs., %), normal grains (Ng, %), cooking time (Ct, min:s), concentrations of potassium (K, g kg^{-1} of dry matter – DM), phosphorus (P, g kg^{-1} DM), calcium (Ca, g kg^{-1} DM), magnesium (Mg, g kg^{-1} DM), iron (Fe, mg kg^{-1} DM), zinc (Zn, mg kg^{-1} DM) and copper (Cu, mg kg^{-1} DM) in grains of 17 common bean genotypes evaluated in the dry and rainy seasons of 2019

	DF	Mean square					
		L*	a*	b*	M100G	Length	Width
Block/environment	4	3.12	0.21	1.43	5.57	0.05	0.03
Genotype (G)	16	1,810.27*	49.61*	397.61*	42.66*	3.23*	0.40*
Environment (E)	1	2.92^{ns}	7.23*	88.83*	359.42*	5.48*	2.81*
G x E	16	12.66*	1.78*	4.06*	8.51*	0.31*	0.08*
Error	64	1.58	0.25	1.06	3.15	0.13	0.04
Mean		40.11	4.40	7.91	23.52	10.39	6.38
CEV (%)		3.13	11.42	13.05	7.55	3.48	2.98
SA		1.00	1.00	1.00	0.96	0.98	0.95

Continuation table 1

		Thickness	Abs.	Ng	Ct	K	P
Block/environment	4	0.06	0.10	0.11	50,365.99	9.76	0.85
Genotype (G)	16	0.21*	2.66*	0.65*	128,981.22*	2.71*	0.51*
Environment (E)	1	1.66*	14.43*	0.16ns	237,896.82ns	1.20ns	66.26*
G x E	16	0.05ns	2.92*	0.53*	79,155.59*	1.02ns	0.51*
Error	64	0.04	0.43	0.17	20,885.62	1.06	0.21
Mean		4.58	93.37	94.98	16:10	12.59	5.48
CEV (%)		4.60	6.95	4.23	14.89	8.17	8.29
SA		0.89	0.92	0.86	0.92	0.78	0.77
		Ca	Mg	Fe	Zn	Cu	
Block/environment	4	0.01	0.03	109.83	5.62	5.07	
Genotype (G)	16	0.21*	0.05*	165.81*	16.97ns	1.55ns	
Environment (E)	1	46.32*	24.04*	15,688.48*	2.99ns	258.95*	
G x E	16	0.17*	0.03*	199.04*	30.07*	2.82ns	
Error	64	0.07	0.01	32.41	15.24	1.63	
Mean		1.75	1.35	63.24	24.26	8.10	
CEV (%)		15.17	8.60	9.00	16.09	15.77	
SA		0.81	0.85	0.90	0.32	0.00	

*: Significant by the F test at 0.05 probability. ns: non-significant

Black bean genotypes had the lowest L*, a* and b* values (Table 2), showing the lowest lightness among the evaluated grain types, without having a secondary color (a* and b* values close to zero). All black bean genotypes exhibited L* ≤ 22.00 in the dry season, which is the color pattern used in the selection of superior genotypes (RIBEIRO *et al*., 2021), because it characterizes the absence of purplish grains (RIBEIRO; POSSEBOM; STORCK, 2003). However, the black bean genotypes showed greater lightness (L* > 22.00) in the rainy season, indicating the presence of purplish grains, which is usually associated with longer cooking time. Higher average air temperature and solar radiation are recorded in the growing rainy season and these climatic factors may have contributed to increase of incidence of purplish grains in the black bean genotypes.

The L*, a* and b* values did not allow a clear differentiation between the carioca, pink and cranberry common bean genotypes by the grain color in the two growing seasons. The carioca common bean genotypes showed L*, a* and b* values within the range of variation described for this grain type (POSSOBOM *et al*., 2015; RIBEIRO; KLÄSENER, 2020). However, only the lines LEC 04-16 and UEM 266 exhibited the recommended color pattern for carioca beans in the two growing seasons, that is, very light grains (L* ≥ 55.00), with slightly red (a* ≤ 7.00) and slightly yellow (b* ≤ 16.00) shades (ARNS *et al*., 2018). The grain color of carioca common bean lines LEC 04-16 and UEM 266 meets the objectives of today's breeding programs. New carioca common bean cultivars with very light grains are highly appreciated by consumers in Brazil. Therefore, it have higher market demand.

The line CNFRJ 15411 exhibited the highest mass of 100 grains in the two growing seasons. The evaluated common bean genotypes are characterized by having small (< 25 g) or medium-sized (25 to 40 g) grains, according to the classes described by Hegay *et al*. (2014), being representative of the most produced grain sizes in Brazil. The line SM 05 11 had the highest grain length and width values in the dry season and the lines LEC 04-16 and UEM 266 showed the lowest grain width values in the rainy season. On the other hand, the line CNFRJ 15411 stood out in relation to the grain length in the rainy season and the grain thickness in the average of the two growing seasons. Wide genetic variability for mass of 100 grains and grain dimensions have been reported for common bean genotypes (HERRERA-HERNÁNDEZ *et al*., 2018; RIBEIRO *et al*., 2021; RIVERA *et al*., 2016) and this enables the selection of new lines with differentiated grain sizes that can add value in their commercialization.

The lines SM 1510, TB 17-03 and LEC 04-16 showed the highest absorption values in the two growing seasons (≥ 99.18%), evidencing that it is possible to select common bean lines with grains that absorb more water regardless of the growing season, confirming previous results obtained by Perina *et al*. (2014). However, most common bean genotypes exhibited normal grain values close to 100% in both growing seasons (Table 3), indicating that breeding programs have concentrated efforts in the development of common bean lines that do not have hard grains.

Table 2 - Means of the traits of L* value (L*), a* value (a*), b* value (b*), mass of 100 grains (M100G, g), grain length (Length, mm), grain width (Width, mm), grain thickness (Thickness, mm) and absorption (%) of 18 common bean genotypes evaluated in the dry and rainy seasons of 2019

	Type[1]	L*		a*		b*		M100G	
		dry	rainy	dry	rainy	dry	rainy	dry	rainy
CHP 04-239-01	B	21.49 c*	23.44 c	1.97 f	1.43 e	0.91 d	-1.67 d	23.67 c	22.63 a
TB 17-02	B	21.02 c	23.77 c	1.26 f	1.11 e	1.06 d	-1.35 d	23.53 c	21.97 a
CHP 01-182-12	B	20.73 c	23.68 c	1.74 f	1.28 e	0.94 d	-3.58 d	21.90 c	20.07 b
BRS Intrépido	B	20.41 c	23.14 c	1.57 f	1.32 e	1.23 d	-1.94 d	26.37 b	19.20 b
LP 13-624	B	21.97 c	23.02 c	2.29 e	1.78 e	1.19 d	-2.00 d	23.75 c	21.90 a
SM 1510	B	20.31 c	22.80 c	1.69 f	1.36 e	1.36 d	-1.86 d	25.40 b	20.20 b
TB 17-03	B	21.49 c	23.22 c	1.21 f	1.14 e	1.54 d	-1.35 d	24.13 c	21.67 a
Fepagro Triunfo	B	21.35 c	24.26 c	2.88 e	2.14 e	0.94 d	-1.87 d	25.91 b	23.43 a
CNFRS 15558	P	56.93 a	54.16 b	8.50 b	8.14 b	15.63 b	17.77 a	29.43 b	23.60 a
CNFRJ 15411	CR	55.28 b	52.63 b	8.77 b	10.33 a	12.52 c	12.20 c	35.53 a	26.17 a
Fepagro Garapiá	C	55.26 b	54.12 b	6.22 c	7.42 b	18.04 a	15.70 b	23.47 c	23.23 a
Linhagem 110	C	58.89 a	54.64 b	5.38 d	7.81 b	15.39 b	15.68 b	26.40 b	22.07 a
FAP-F3-2 SEL	C	58.90 a	54.08 b	6.48 c	7.64 b	16.65 b	14.85 b	26.07 b	22.23 a
Pérola	C	58.77 a	54.67 b	5.70 c	7.33 b	16.24 b	15.42 b	27.27 b	23.93 a
LEC 04-16	C	56.39 b	57.31 a	4.73 d	5.15 d	15.28 b	12.88 c	21.73 c	17.90 c
UEM 266	C	57.64 a	55.44 b	4.62 d	6.52 c	15.87 b	14.17 c	20.57 c	17.17 c
LP 13-84	C	57.94 a	54.63 b	5.31 d	7.46 b	15.50 b	15.51 b	26.57 b	20.50 b
SM 05 11	C	54.13 b		9.73 a		17.78 a		37.53 a	
Mean		41.05	39.94	4.45	4.67	9.34	6.97	26.07	21.64

Genotype	Type[1]	Length		Width		Thickness	Absorption	
		dry	rainy	dry	rainy	mean	dry	rainy
CHP 04-239-01	B	10.24 d	10.14 b	6.40 c	6.30 a	4.50 c	85.92 b	101.69 a
TB 17-02	B	9.85 d	9.76 c	6.29 c	6.22 a	4.56 c	71.85 b	92.03 b
CHP 01-182-12	B	9.62 d	9.31 c	6.36 c	6.14 a	4.36 c	42.54 c	93.51 b
BRS Intrépido	B	10.98 c	9.73 c	6.80 b	6.10 a	4.45 c	118.92 a	71.14 c
LP 13-624	B	10.06 d	9.92 c	6.56 b	6.28 a	4.59 c	85.14 b	103.00 a
SM 1510	B	11.27 c	9.78 c	6.50 c	6.04 a	4.49 c	106.09 a	111.87 a
TB 17-03	B	10.82 c	10.45 b	6.60 b	6.56 a	4.40 c	107.82 a	99.18 a
Fepagro Triunfo	B	10.79 c	10.19 b	6.75 b	6.27 a	4.61 c	92.77 b	92.36 b
CNFRS 15558	P	11.14 c	10.83 b	6.75 b	6.65 a	4.80 b	48.77 c	97.76 a
CNFRJ 15411	CR	13.28 b	12.11 a	6.84 b	6.31 a	5.15 a	80.22 b	113.26 a
Fepagro Garapiá	C	10.32 d	10.38 b	6.28 c	6.27 a	4.66 c	88.19 b	91.96 b
Linhagem 110	C	10.17 d	10.10 b	6.68 b	6.34 a	4.51 c	92.88 b	83.94 b
FAP-F3-2 SEL	C	10.24 d	10.24 b	6.63 b	6.55 a	4.57 c	90.39 b	104.32 a
Pérola	C	11.19 c	10.45 b	6.90 b	6.39 a	4.67 c	81.73 b	94.11 b
LEC 04-16	C	9.95 d	9.59 c	6.16 c	5.61 b	4.45 c	107.40 a	99.37 a
UEM 266	C	9.71 d	9.36 c	6.11 c	5.39 b	4.40 c	75.64 b	109.47 a
LP 13-84	C	10.94 c	10.35 b	6.78 b	6.31 a	4.61 c	52.02 c	87.24 b
SM 05 11	C	14.61 a		7.65 a		4.50 c	83.52 b	
Mean		10.84	10.16	6.61	6.22	4.58	89.55	96.84

[*] Means followed by same letter in a column constitute a homogeneous group according to the Scott-Knott´s test at 5% probability. [ns] = non-significant.
[1]Type: B: black beans; P: pink beans; CR: cranberry beans; C: carioca beans

Table 3 - Means of the traits of normal grains (Ng, %), cooking time (Ct, min:s), concentrations of potassium (K, g kg^{-1} of dry matter – DM), phosphorus (P, g kg^{-1} DM), calcium (Ca, g kg^{-1} DM), magnesium (Mg, g kg^{-1} DM), iron (Fe, mg kg^{-1} DM), zinc (Zn, mg kg^{-1} DM) and copper (Cu, mg kg^{-1} DM) in grains of 18 common bean genotypes evaluated in the dry and rainy seasons of 2019

Genotype	Ng		Ct		K	P	
	dry	rainy	dry	rainy	mean	dry	rainy
CHP 04-239-01	97.33 a*	100.00 a	14:59 c	16:50 b	12.31 b	6.07 b	4.69 b
TB 17-02	82.67 b	92.00 a	15:01 c	19:36 a	12.06 b	6.08 b	4.44 b
CHP 01-182-12	98.67 a	97.33 a	15:19 c	18:03 a	11.97 b	6.05 b	4.60 b
BRS Intrépido	94.67 a	86.67 a	13:52 c	18:40 a	13.92 a	6.46 a	4.55 b
LP 13-624	100.00 a	98.67 a	14:12 c	16:16 b	11.75 b	6.63 a	4.59 b
SM 1510	100.00 a	100.00 a	18:41 b	16:04 b	12.07 b	6.03 b	4.31 b
TB 17-03	98.67 a	98.67 a	14:53 c	17:43 a	13.48 a	6.42 a	4.90 a
Fepagro Triunfo	100.00 a	100.00 a	11:45 c	16:29 b	12.66 b	5.93 b	4.41 b
CNFRS 15558	65.33 c	96.00 a	28:09 a	20:07 a	13.69 a	6.57 a	5.74 a
CNFRJ 15411	100.00 a	100.00 a	20:46 b	16:25 b	11.64 b	5.73 b	5.39 a
Fepagro Garapiá	98.67 a	92.00 a	13:41 c	16:54 b	12.41 b	5.92 b	3.89 b
Linhagem 110	98.67 a	89.33 a	12:25 c	19:18 a	12.93 a	6.04 b	4.86 a
FAP-F3-2 SEL	98.67 a	98.67 a	12:08 c	16:04 b	13.24 a	6.64 a	4.45 b
Pérola	92.00 b	90.67 a	12:09 c	16:10 b	12.29 b	7.08 a	4.19 b
LEC 04-16	100.00 a	90.67 a	15:46 c	14:14 b	12.68 b	6.28 b	5.24 a
UEM 266	100.00 a	100.00 a	12:30 c	15:07 b	12.70 b	6.63 a	4.88 a
LP 13-84	84.00 b	89.33 a	15:00 c	14:38 b	12.21 b	6.24 b	4.27 b
SM 05 11	100.00 a		12:33 c		12.31 b	5.44 b	
Mean	94.96	95.30	15:13	16:59	12.59	6.24	4.67

Genotype	Ca		Mg		Fe		Zn		Cu
	dry	rainy	dry	rainy	dry	rainy	dry	rainy	mean
CHP 04-239-01	2.39 a	1.31 a	0.86 a	1.94 a	69.33 d	52.73 a	23.71 a	20.73 a	8.19^{ns}
TB 17-02	2.46 a	1.50 a	1.01 a	1.98 a	79.67 b	45.53 a	23.61 a	21.00 a	8.08
CHP 01-182-12	2.10 a	1.32 a	0.86 a	1.97 a	73.33 c	50.87 a	24.41 a	24.57 a	7.91
BRS Intrépido	2.66 a	1.16 b	0.89 a	1.64 b	86.33 b	51.20 a	26.52 a	21.07 a	8.12
LP 13-624	2.39 a	0.94 c	0.87 a	1.82 a	96.33 a	50.83 a	28.67 a	21.93 a	7.35
SM 1510	2.33 a	1.10 b	0.92 a	1.81 a	83.33 b	49.37 a	24.31 a	27.03 a	8.56
TB 17-03	2.28 a	1.24 b	0.90 a	1.98 a	67.00 d	54.20 a	26.22 a	21.27 a	9.09
Fepagro Triunfo	2.67 a	1.44 a	0.94 a	1.94 a	67.67 d	67.03 a	25.04 a	21.87 a	8.63
CNFRS 15558	2.22 a	0.58 d	0.76 b	1.65 b	83.33 b	49.97 a	26.49 a	26.07 a	7.35
CNFRJ 15411	2.46 a	0.61 d	0.67 c	1.89 a	75.33 c	42.77 a	20.57 a	31.70 a	7.85
Fepagro Garapiá	2.73 a	1.03 b	0.92 a	1.57 b	59.00 d	42.83 a	24.23 a	19.30 a	7.53
Linhagem 110	2.26 a	0.89 c	0.81 b	1.68 b	76.00 c	49.67 a	23.85 a	27.97 a	8.67
FAP-F3-2 SEL	2.69 a	1.05 b	0.89 a	1.77 b	65.00 d	49.03 a	22.36 a	22.17 a	7.68
Pérola	2.10 a	1.13 b	1.00 a	1.87 a	77.67 b	56.60 a	21.62 a	22.07 a	7.54
LEC 04-16	2.30 a	0.76 c	0.79 b	1.89 a	75.33 c	46.37 a	24.31 a	27.70 a	8.48
UEM 266	2.71 a	0.82 c	0.79 b	1.81 a	85.00 b	49.97 a	25.59 a	25.67 a	8.36
LP 13-84	2.53 a	1.50 a	0.91 a	2.08 a	66.33 d	55.37 a	23.78 a	27.37 a	8.39
SM 05 11	2.56 a		0.70 c		83.33 b		22.77 a		8.19
Mean	2.44	1.08	0.86	1.84	76.07	50.84	24.34	24.09	8.11

* Means followed by same letter in a column constitute a homogeneous group according to the Scott-Knott´s test at 5% probability. ^{ns} = non-significant

The common bean genotypes presented great variation for cooking time, from 11 min and 45 s (Fepagro Triunfo) to 28 min and 09 s (CNFRS 15558). Breeding programs have obtained common bean lines with differences in terms of cooking time (CICHY; WIESINGER; MENDOZA, 2015; DIAS *et al*., 2021; PEREIRA *et al*., 2019; SILVA *et al*., 2018). However, fast cooking common bean lines, that is, less than 25 min (SANTOS; RIBEIRO; MAZIERO, 2016) are more likely to be accepted by consumers who started to prepare their meals at home during the coronavirus pandemic. All common bean genotypes evaluated in the present study are fast cooking, except for the line CNFRS 15558 in the dry season. These results demonstrate that breeding programs have prioritized the development of fast cooking common bean lines of different grain types.

The Scott-Knott test stratified common bean genotypes into two groups for potassium concentration, at the average of the two seasons. The genotypes BRS Intrépido, TB 17-03, CNFRS 15558, Linhagem 110 and FAP-F3-2 SEL were grouped into the cluster with the highest potassium concentrations ($\geq$ 12.93 g kg^{-1} of dry matter - DM) and the other genotypes were part of the cluster with the lowest potassium concentrations ($\leq$ 12.70 g kg^{-1} DM). A similar amplitude of variation was described for common bean genotypes of different grain types (DELFINI *et al*., 2020; JAN *et al*., 2021; MCCLEAN *et al*., 2017) and shows that it is possible to select lines with higher potassium concentration in the grains. All common bean genotypes evaluated in this study showed a high K concentration ($\geq$ 12 g kg^{-1} DM) according with the classes proposed by Steckling *et al*. (2017), except the line CHP 01-182-12. The inclusion of common bean cultivars with high K concentration in the diet could confer protective health effects since this nutrient contributed to decrease cases of hypertension (MCDONOUGH; YOUN, 2017).

Three common bean lines stood out for phosphorus concentration (TB 17-03, CNFRS 15558 and UEM 266) and nine genotypes exhibited the highest magnesium concentration values (CHP 04-239-01, TB 17-02, CHP 01-182-12, LP 13-624, SM 1510, TB 17-03, Fepagro Triunfo, Pérola and LP 13-84) in the two growing seasons. Similarly, it was possible to select common bean genotypes with higher phosphorus and magnesium concentrations at different growing seasons, despite the fact that a significant genotype x environment interaction was observed for these minerals (RIBEIRO *et al*., 2021; RIBEIRO; KLÄSENER, 2020). In this study, higher phosphorus concentration values were obtained in the dry season and higher magnesium concentration values were registered in the rainy season, showing that climatic factors, such as temperature, precipitation and solar radiation can influence uptake, transport and accumulation of these minerals in grains. Despite that, the lines CNFRS 15558, CNFRJ 15411 and LEC 04-16 exhibited high phosphorus concentration, which was defined as $\geq$ 5 g kg^{-1} DM (STECKLING *et al.*, 2017), in two growing season. The phosphorus is required for bone mineralization (SERNA; BERGWITZ, 2020), therefore a diet rich in this mineral is beneficial for protection fractures. None common bean genotype exhibited high magnesium in two growing seasons, i. e., $\geq$ 2 g kg^{-1} DM as defined by Ribeiro and Mezzomo (2020). Therefore, the selection of common bean lines with higher phosphorus and magnesium concentrations must be validated in experiments conducted in various environments.

Common bean genotypes were grouped into a single cluster by the Scott-Knott test for the concentrations of calcium, iron and zinc in one or both growing seasons, although a significant effect for genotype and/ or a significant genotype x environment interaction was observed for these minerals (Table 1). These results evidence the difficulty of selecting superior common bean lines for the grain quality traits and mineral concentration based on results obtained in the grouping of means. The use of selection index, considering the data from two growing seasons, is an alternative to increase the efficiency of simultaneous selection of several traits.

Selection of light-grain common bean lines with high grain quality and mineral concentration

Heritability ranging from 28.31 to 97.87% was observed for the evaluated traits (Table 4), i. e., it varied from low to high, according to the classes proposed by Soltani *et al*. (2016). Heritability estimates variable in magnitude were described for grain quality traits (ARNS *et al*., 2018; RIBEIRO *et al*., 2021) and mineral concentration (KATUURAMU *et al*., 2018; RIBEIRO *et al*., 2021) in common bean genotypes. High heritability ($\geq$ 60.00%) was obtained for 14 traits in the present study, indicating that most of the evaluated traits had high genetic variability and this provides greater ease for the selection of light-grain common bean lines with high grain quality and mineral concentration.

The highest genetic gain estimates were observed for the a* value (-13.50%) and cooking time (-7.85%), demostrating that the greatest gains were observed in the decrease of the red shade of the grains and in the cooking time of the light-grain common bean lines. Similarly, Arns *et al*. (2018) obtained a negative genetic gain for these two traits in the selection of slow darkening carioca common bean lines. Genetic gain favorable to the selection objectives was also observed for the other traits evaluated in the present study, except for the mass of 100 grains, length, width, thickness and calcium concentration. Therefore, the use of the rank-sum index allowed selection of the four superior common bean genotypes for most of the grain quality traits and mineral concentration: Pérola, LEC 04-16, Linhagem 110 and UEM 266 (all carioca beans).

Table 4 - Average of the original population (X_0), average of selected genotypes (Xs), heritability (h^2%), genetic gain (GG) and percentage of genetic gain (GG%) with simultaneous selection by the rank-sum index for the traits of L* value (L*), a* value (a*), b* value (b*), mass of 100 grains (M100G, g), grain length (Length, mm), grain width (Width, mm), grain thickness (Thickness, mm), absorption (Abs., %), normal grains (Ng, %), cooking time (Ct, min:s), concentrations of potassium (K, g kg^{-1} of dry matter - DM), phosphorus (P, g kg^{-1} DM), calcium (Ca, g kg^{-1} DM), magnesium (Mg, g kg^{-1} DM), iron (Fe, mg kg^{-1} DM), zinc (Zn, mg kg^{-1} DM) and copper (Cu, mg kg^{-1} DM) of light- and dark-grain common bean genotypes selected in the two growing seasons of 2019

Trait	X_0	X_S	h^2%	GG	GG%	Pérola	LEC 04-16	Linhagem 110	UEM 266
Selection of light-grain common bean genotypes									
L*	55.98	56.72	63.68	0.47	0.84	56.72	56.85	56.77	56.54
a*	6.86	5.90	96.86	-0.93	-13.50	6.52	4.94	6.59	5.57
b*	15.29	15.12	91.04	-0.16	-1.06	15.83	14.08	15.53	15.02
M100G	24.10	22.13	94.82	-1.87	-7.76	25.60	19.82	24.23	18.87
Length	10.57	10.06	97.87	-0.50	-4.73	10.82	9.77	10.14	9.53
Width	6.38	6.20	94.07	-0.18	-2.77	6.65	5.89	6.51	5.75
Thickness	4.65	4.51	84.99	-0.12	-2.54	4.67	4.45	4.51	4.41
Abs.	88.82	92.22	81.23	0.21	2.30	87.92	103.39	88.14	92.55
Ng	93.56	94.84	66.39	0.05	0.57	91.33	95.33	94.00	100.00
Ct	16:12	15:00	85.34	-76.30	-7.85	14:10	15:00	15:51	13:49
K	12.64	12.65	46.71	0.00	0.02	12.29	12.68	12.93	12.70
P	5.56	5.65	72.45	0.07	1.18	5.64	5.76	5.45	5.75
Ca	1.69	1.62	68.49	-0.04	-2.67	1.62	1.53	1.58	1.76
Mg	1.32	1.33	65.24	0.01	0.59	1.44	1.34	1.25	1.30
Fe	61.42	64.57	79.43	2.50	4.08	67.13	60.85	62.83	67.48
Zn	24.60	24.85	28.31	0.07	0.28	21.84	26.01	25.91	25.63
Trait	X_0	X_S	h^2%	GG	GG%	BRS Intrépido	TB 17-03	SM 1510	Fepagro Triunfo
Selection of dark-grain common bean genotypes									
L*	22.26	22.12	19.09	-0.02	-0.11	21.78	22.36	21.56	22.81
a*	1.63	1.66	89.43	0.02	1.49	1.44	1.18	1.52	2.51
b*	-0.40	-0.25	0.00	0.00	0.00	-0.36	0.09	-0.25	-0.47
M100G	22.86	23.29	59.58	0.26	1.12	22.78	22.90	22.80	24.67
Length	10.18	10.50	83.83	0.27	2.62	10.35	10.64	10.53	10.49
Width	6.39	6.45	70.99	0.05	0.74	6.45	6.58	6.27	6.51
Thickness	4.49	4.49	23.85	-0.00	-0.04	4.45	4.40	4.50	4.61
Abs.	98.49	109.71	90.11	0.38	3.95	95.03	103.50	108.98	92.57
Ng	96.58	97.18	89.52	0.04	0.38	90.67	98.67	100.00	100.00
Ct	16:09	16:02	79.47	-6.39	-0.66	16:16	16:18	17:23	14:07
K	12.53	13.03	71.60	0.36	2.89	13.93	13.48	12.07	12.66
P	5.38	5.38	0.00	0.00	0.00	5.51	5.66	5.17	5.17
Ca	1.83	1.86	46.08	0.01	0.75	1.91	1.76	1.72	2.06
Mg	1.39	1.38	67.50	-0.01	-0.87	1.27	1.44	1.37	1.44
Fe	65.30	65.77	75.65	0.35	0.54	68.77	60.60	66.35	67.35
Zn	23.87	24.16	0.00	0.00	0.00	23.80	23.74	25.67	23.45

The lines LEC 04-16, Linhagem 110 and UEM 266 showed L*, a* and b* values similar to Pérola, which is the most produced common bean cultivar in Brazil, and meeting the grain color pattern proposed for carioca beans by Arns *et al*. (2018). They also exhibited higher absorption and normal grain values compared to the cultivar Pérola and stood out for their fast cooking time, according to the criterion defined by Santos, Ribeiro and Maziero (2016). These lines and the cultivar Pérola have a high concentrations of potassium (≥ 12.29 g kg^{-1} DM), phosphorus (≥ 5.45 g kg^{-1} DM), calcium (≥ 1.53 g kg^{-1} DM) and iron (≥ 60.85 mg kg^{-1} DM), according to the classes established by Steckling *et al*. (2017), Ribeiro *et al*. (2013) and Tryphone and Nchimbi-Msolla (2010), respectively. The selection of new common bean lines with high mineral concentration and the inclusion of these in the diet can represent health benefits. This is because potassium helps in the control of hypertension (MCDONOUGH; YOUN, 2017), phosphorus and calcium have a protective role in bone health (LI *et al*., 2018; SERNA; BERGWITZ, 2020) and iron acts in the prevention of anemia (DEV; BABITT, 2017).

The lines LEC 04-16, Linhagem 110 and UEM 266 and the cultivar Pérola were superior to the other light-grain common bean genotypes evaluated for several grain quality traits and mineral concentration, so they are promising for use in the breeding program and in food. The genetic superiority of these new carioca bean lines needs to be validated in experiments conducted in a greater number of environments.

Selection of dark-grain common bean lines with high grain quality and mineral concentration

High heritability (≥ 60.00%) was obtained for nine traits (Table 4), showing that a lower number of grain quality traits and mineral concentration had high genetic variability in dark-grain common bean lines. Additionally, a lower magnitude of genetic gain was observed for the evaluated traits in comparison with the values obtained in the selection of light-grain common bean lines. These results indicate that the black-common bean lines evaluated in the 2018 and 2019 biennium in the Southern region of Brazil have a narrow genetic base.

The highest values of genetic gain were obtained for absorption (3.95%), potassium concentration (2.89%) and grain length (2.62%), i. e., the highest increases were observed for these traits when the selection of superior dark-grain common bean lines was performed. A genetic gain in a direction favorable to the selection objectives for high grain quality and mineral concentration was verified for most evaluated traits, similarly to what was described in the present study in the selection of light-grain common bean lines.

The four black common bean genotypes selected by the rank-sum index were BRS Intrépido, TB 17-03, SM 1510 and Fepagro Triunfo. The lines TB 17-03 and SM 1510 exhibited L*, a* and b* values similar to the cultivars BRS Intrépido and Fepagro Triunfo, but only the line SM 1510 has a L* value ≤ 22.00, that is, it meets the recommended grain color pattern for black beans (RIBEIRO; POSSEBOM; STORCK, 2003). The lines TB 17-03 and SM 1510 have a very similar mass of 100 grains, grain dimensions, absorption and normal grains to those observed in the cultivars BRS Intrépido and Fepagro Triunfo. In addition, the four selected genotypes stood out for their fast cooking time (≤ 16 min and 18 s) and for the high concentrations of potassium (≥ 12.07 g kg^{-1} DM), phosphorus (≥ 5.17 g kg^{-1} DM), calcium (≥ 1.72 g kg^{-1} DM) and iron (≥ 60.60 mg kg^{-1} DM). The lines TB 17-03 and SM 1510 and the cultivars BRS Intrépido and Fepagro Triunfo showed superiority for several grain quality traits and mineral concentration, therefore, they have potential for use in breeding and nutrition, which still needs to be evaluated in relation to the stability of these traits.

The rank-sum index with the use of differentiated economic weights that represent the order of preference of consumers for the different grain quality traits and mineral concentration was efficient to select superior carioca and black common bean lines for most of the evaluated traits. Dias *et al*. (2021) and Silva *et al*. (2018) observed that the rank-sum index, with different economic weights assigned, also resulted in the selection of superior common bean lines for most of the analyzed traits, validating the results obtained in the present study. These results reinforce the difficulty of selecting superior common bean lines for all the traits considered important in the breeding program. In the present study, the application of rank-sum index allowed the selection of new carioca and black common bean lines with high grain quality and mineral concentration, that is, with attributes highly valued by common bean consumers, which increases their probability of acceptance and use in food.

CONCLUSIONS

1. The common bean lines and cultivars has genetic variability for all grain quality traits and mineral concentration, except for copper concentration;
2. Four carioca (LEC 04-16, Linhagem 110, UEM 266 and Pérola) and four black (TB 17-03, SM 1510, BRS Intrépido and Fepagro Triunfo) common bean genotypes are superior for several grain quality traits and have high concentrations of potassium, phosphorus, calcium and iron, showing potential for use in breeding and nutrition.

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