http://doi.org/10.1590/1678-992X-2021-0223

Scientia Agricola

ISSN 1678-992X

Research Article

Environmental variability in simultaneous selection of common bean for grain quality and mineral concentration traits

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Edited by: Leonardo Oliveira Medici

Received September 09, 2021
Accepted December 26, 2021

ABSTRACT: The selection of common bean (*Phaseolus vulgaris* L.) lines based on grain quality and mineral concentration traits will be more efficient if a minimum number of experiments is established. This study was carried out to determine whether grain quality and mineral concentration traits are significantly affected by the genotype × environment interaction; to estimate heritability and genetic gain in individual and combined experiments; and to select superior common bean lines considering a minimum number of experiments. A total of 17 common bean genotypes were evaluated in four experiments. Grain quality was determined through seven traits, and the concentration of six minerals was analyzed by acid digestion. Statistical analyses were completed using data obtained from both individual (I, II, III and IV) and combined (I and II; I, II and III; and I, II, III and IV) experiments. Except for the potassium concentration, all traits showed a significant genotype × environment interaction effect. Heritability and genetic gain estimates of grain quality and mineral concentration traits varied when the data were obtained from one or more experiments. Genetic gain may be inflated because of the data being based on one or two experiments. Four carioca bean (BRS MG Uai, LP 09-33, LEC 01-16 and Pérola) and four black bean (TB 02-19, CHP 04-239-52, TB 03-11 and IAC Netuno) genotypes were selected for their high grain quality and mineral concentration based on four experiments. Data from at least four experiments should be used to select common bean lines superior in grain quality and mineral concentration traits to increase the efficiency of simultaneous selection.

Keywords: *Phaseolus vulgaris*, genotype × environment interaction, multiplicative index

Introduction

The common bean (*Phaseolus vulgaris*) has high nutritional value and functional properties that provide several health benefits (Chávez-Mendoza and Sánchez, 2017; Messina, 2014; Suárez-Martínez et al., 2016). From a nutritional standpoint, the common bean is one of the most important dietary sources of minerals, especially potassium, magnesium, calcium, iron, zinc and copper (Di Bella et al., 2016).

Mineral concentrations in common bean vary by genotype, environment and genotype × environment interaction (Dias et al., 2021; Ribeiro et al., 2021; Steckling et al., 2017). Thus, the selection of superior common bean lines based on data obtained from a single experiment is unrepresentative of the genetic diversity of the germplasm. The environmental variability between seasons and years in the same growing location must be considered so that simultaneous selection for mineral concentration is efficient.

Simultaneous selection of grain quality and mineral concentration traits in common bean has recently emerged as a breeding program goal. Common bean genotypes with high grain quality (Silva et al., 2018) and high mineral concentration (Zanotti et al., 2020) were selected according to the rank-sum index based on data obtained from a single experiment. Using data from three experiments in a multiplicative index analysis, Ribeiro et al. (2021) selected mineral-biofortified light- and dark-grained cultivars of common bean of high grain quality. Dias et al. (2021) identified carioca bean lines of high grain quality and high micromineral concentration using data from nine experiments analyzed according to the rank-sum index. None of these studies described the criterion used to define the number of experiments employed in simultaneous selection.

Identifying the minimum number of experiments to be used in the simultaneous selection of consumer-focused quality parameters represents an essential innovation for common-bean breeding programs. Therefore, this study proposes to (1) determine whether grain quality and mineral concentration traits are significantly affected by the genotype × environment interaction; (2) obtain broad sense heritability and genetic gain estimates for these traits when evaluated in both individual and combined experiments; and (3) select superior carioca and black bean lines considering a minimum number of experiments that will ensure greater efficiency in simultaneous selection.

Materials and Methods

Description of experiments

Four Value for Cultivation and Use (VCU) experiments with common bean from the 2016 and 2017 biennium were carried out in the area of the Common-Bean Breeding Program, in Santa Maria, in the state of Rio Grande do Sul (RS), Brazil (29°42′ S, 53°43′ W, altitude

95 m). The experiments were conducted in the following combinations of growing seasons and years: 2016 rainy-season crop (I), 2017 dry-season crop (II), 2017 rainy-season crop (III) and 2018 dry-season crop (IV). Sowing was carried out in Oct (rainy-season crop) and Feb (dry-season crop), meeting the current rules for the registration of new common bean cultivars in Brazil (MAPA, 2006). The climate in the region is a humid subtropical type (Alvares et al., 2013).

The experiments were carried out in a randomized-block design with three replicates. The experimental plot consisted of four 4-m rows spaced 0.5 m apart. However, only the two central rows constituted the usable area (4 m^2), to avoid mixing the seeds. The evaluated treatments were 17 common bean genotypes, consisting of nine carioca beans (beige seed coat with brown streaks): SM 0312, BRS MG Uai, CNFC 15 097, LEC 02-16, GEN 45-2F-293P, LP 09-33, LEC 01-16, Pérola and Carioca; and eight black beans: IAC Netuno, LP 11-117, TB 02-19, CHP 04-239-52, CHP 01-182-48, TB 03-11, BRS Valente and Guapo Brilhante. Cultivars Pérola, Carioca, BRS Valente and Guapo Brilhante are registered for cultivation in the state of Rio Grande do Sul; thus, they were considered as controls. The other evaluated lines were obtained by different public research institutions that integrated the VCU of the southern Brazilian common bean network of the 2016 and 2017 biennium. These lines are also being evaluated for agronomic traits for registering new common bean cultivars in the National Registry of Cultivars in Brazil (MAPA, 2006). All genotypes have grains from the Mesoamerican gene pool of the most produced and consumed commercial types in Brazil (carioca and black).

The experimental area was cultivated with black oats during the off-season months, and in Oct, it was prepared by the conventional cultivation system for the sowing of common bean. The amount of fertilizer was calculated based on the interpretation of a chemical analysis of the soil, which is classified as a typic alitic Argisol, Hapludalf. Management practices (fertilization and control of weeds and insects) were implemented as recommended for the common bean crop in the southern region of Brazil (CTSBF, 2012).

The plants were harvested manually at the maturation stage (R9) of each genotype. Plants harvested from each usable plot were tied together and identified with a tag. These plants remained in a greenhouse until the grains could be threshed. Grain moisture was standardized at 13 % to determine grain quality traits.

Evaluation of grain quality and mineral concentration

The grains were kept under refrigeration (at a temperature of 5 °C and relative humidity of 75 %) until analysis. Grain quality was evaluated based on color, cooking and grain size. A portable colorimeter (CR 410) was used to identify grain color by measuring the L*, a* and b* values. The L* value represented the lightness of the sample, and ranged from 0 (black, characterizing dark grains) to 100 (white, characterizing light grains). The a* value measured the variation between green (–60) and red (+60) colors, whereas the b* value quantified the variation from blue (–60) to yellow (+60) (Bernardo, 2010).

Cooking was assessed by analyzing the traits of absorption, normal grains and cooking time. For this purpose, 25 grains/replicate sample was soaked in 50 mL of distilled water for 8 h at room temperature (20 ± 2 °C). The water was removed and the grains partially dried with a paper towel. Absorption was calculated by the following expression:

$$\text{absorption} = [(\text{weight of grains after absorption} - \text{weight of grains before absorption})/\text{weight of grains before absorption}] \times 100 \quad (1)$$

Normal grains, i.e., grains that absorbed water after soaking, were counted and expressed as a percentage. Cooking time was evaluated in a 25-plunger Mattson cooker, as described by Ribeiro et al. (2021). The time necessary for the drop of each plunger of the Mattson cooker was recorded and the average drop time of the first 13 plungers was considered the cooking time of each sample.

Grain size was determined based on mass of 100 grains (g), considering the average weight obtained of three samples of 100 grains deemed representative of each replicate. Grains were classified as small (< 25 g), medium (25 to 40 g), large (40 to 60 g) and very large (> 60 g) (Hegay et al., 2014).

The concentration of four macrominerals (potassium, phosphorus, calcium and magnesium) and two microminerals (iron and copper) was quantified in a 30-g sample of dry and ground grains collected randomly from each usable plot. A 0.5-g aliquot of this sample was used for acid digestion, following the same methodology described by Ribeiro et al. (2021). The reading of these minerals was performed in an atomic absorption spectrophotometer (AAnalyst 200), except for potassium, which was evaluated in a flame photometer (B262), and phosphorus, which was determined in an optical emission spectrophotometer (AA-7000).

Statistical analyses

The data obtained in each of the four experiments were subjected to analysis of variance, and Hartley's maximum F test checked the homogeneity of residual variances. The traits expressed in percentage terms (normal grains and absorption) were transformed using the expression:

$$\sqrt{x + 0.5} \quad (2)$$

in which *x* is the trait value.

Combined analysis of variance was performed in the following experiments: I and II (2016 rainy and

2017 dry seasons), I, II and III (2016 rainy, 2017 dry and 2017 rainy seasons) and I, II, III and IV (2016 rainy, 2017 dry, 2017 rainy and 2018 dry seasons). In these analyses, the genotype effect was considered fixed and the other effects were considered random. The residual variance was considered heterogeneous when the ratio between the highest and lowest residual mean squares was greater than seven. In this case, the degrees of freedom of the error and the genotype × experiment interaction were corrected in a combined analysis of variance (Cruz, 2016).

The phenotypic correlation matrix obtained from a combined analysis of variance for experiments I, II, III and IV was used to diagnose multicollinearity. Collinearity classes were evaluated according to the criteria of Montgomery et al. (2012). When severe (condition number, CN > 1000) or moderate to strong (100 < CN < 1000) collinearity was detected, highly correlated traits and those with greater weight in the last eigenvectors were identified and excluded until weak collinearity (CN < 100) was reached.

Selection index analyses were compiled from data obtained in seven situations, namely, individual (I, II, III and IV) and combined (I and II; I, II and III; and I, II, III and IV) experiments. The multiplicative index (Subandi et al., 1973) was applied to each of these situations to obtain broad sense heritability and selection gain estimates, and to select the eight superior common bean lines for grain quality and mineral concentration. For the selection of four carioca bean lines, the inverse selection was considered for cooking time and direct selection for the other traits. For the selection of four black bean lines, the inverse selection was carried out for the L* value and cooking time, and direct selection for the other traits. The coincidence percentage of carioca and black bean genotypes selected by the multiplicative index was obtained for all combinations of experiments, both individual (I, II, III and IV) and combined (I and II; I, II and III; and I, II, III and IV). All statistical analyses were compiled using Genes (Cruz, 2016) software.

Results and Discussion

Analysis of variance in individual and combined experiments

Individual analyses of variance revealed a significant genotype effect for all traits evaluated in one or more experiments (Table 1). Therefore, genetic variability was observed for the grain quality and mineral concentration traits (Table 2), confirming the previous results observed in common bean genotypes of different grain types (Dias et al., 2021; Ribeiro et al., 2021; Steckling et al., 2017). These results favor the selection of mineral-biofortified carioca and black bean lines of high grain quality.

However, 12 traits showed a significant genotype × experiment (environment) interaction effect (Table 1), corresponding to 92.3 % of the traits evaluated in the different combined analyses of variance. Similar results were described for grain quality and/or mineral concentration traits when common bean genotypes were evaluated in different experiments (Arns et al., 2018; Dias et al., 2021; Hossain et al., 2013; Ribeiro et al., 2021; Steckling et al., 2017). A significant genotype × environment interaction effect shows that the common bean genotypes varied in grain quality and mineral concentration traits as a function of growing season

Table 1 – Mean square values of genotype (G), experiment (E) and G × E interaction in analysis of variance for the traits of L*, a* and b* values, absorption (Abs), normal grains (Ng), cooking time (Time), mass of 100 grains (M100g) and concentrations of potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) of 17 common bean genotypes evaluated in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

Experiments	L*	a*	b*	Abs	Ng	Time	M100g	K	P	Ca	Mg	Fe	Cu
				%		s	g	g kg^{-1} dry matter				mg kg^{-1} dry matter	
Genotype (G)													
I	782.71*	19.47*	186.20*	2.24*	0.62*	32,178.38*	25.97*	0.74^{ns}	0.38^{ns}	0.12^{ns}	0.07*	178.59^{ns}	3.59*
II	964.70*	8.76*	210.71*	5.15*	2.33*	61,129.08*	57.17 *	0.67^{ns}	0.08^{ns}	0.11^{ns}	0.08^{ns}	268.32*	2.53*
III	995.76*	19.39*	225.57*	1.36*	0.37*	41,761.49*	18.45 *	0.73^{ns}	1.10*	0.33*	0.01^{ns}	62.89*	3.67*
IV	1,035.74*	8.98*	152.65*	0.20^{ns}	0.00^{ns}	19,090.34*	20.55 *	2.28*	0.85^{ns}	0.31*	0.03*	76.38*	1.71*
I and II	1,739.14*	26.76*	395.35*	4.74^{ns}	2.46*	34,938.15^{ns}	62.74 *	0.86^{ns}	0.19^{ns}	0.15^{ns}	0.08^{ns}	245.20^{ns}	4.53*
I, II and III	2,729.28*	45.33*	619.17*	4.60*	2.24*	34,719.04^{ns}	68.75 *	1.20*	0.52^{ns}	0.26^{ns}	0.06^{ns}	182.61^{ns}	3.34^{ns}
I, II, III and IV	3,758.06*	53.32*	767.49*	3.83*	1.71*	26,128.67^{ns}	80.77 *	1.64^{ns}	0.83^{ns}	0.35*	0.04^{ns}	162.12^{ns}	4.09^{ns}
Experiment (E)													
I and II	48.15*	12.19*	18.99*	0.01^{ns}	0.65*	5,285,964.70*	2.79^{ns}	2.18^{ns}	11.88^{ns}	0.01^{ns}	0.77*	639.00^{ns}	26.20*
I, II and III	45.83*	6.51^{ns}	16.69^{ns}	4.92*	0.39*	2,646,085.10*	40.59^{ns}	15.68*	6.29^{ns}	4.98*	29.37*	1,812.55*	776.77*
I, II, III and IV	36.63*	12.14*	32.78*	14.26*	0.88*	3,247,435.26*	570.07*	11.42*	4.59^{ns}	11.02*	34.65*	4,552.31*	570.29*
G × E interaction													
I and II	8.28*	1.48*	1.56*	2.65*	0.50*	58,369.31*	20.39*	0.55^{ns}	0.28^{ns}	0.08^{ns}	0.07*	201.71*	1.58*
I, II and III	6.95*	1.15*	1.66*	2.07*	0.54*	50,174.96*	16.42*	0.47^{ns}	0.52*	0.15*	0.05*	193.90*	3.22*
I, II, III and IV	6.95*	1.10*	3.70*	1.70*	0.70*	42,676.88*	13.79*	0.93^{ns}	0.53*	0.17*	0.05*	188.47*	2.47*

*Significant by F test at 0.05 probability; ^{ns}Non-significant.

Table 2 – Minimum (min) and maximum (max) values, standard deviation (SD) and coefficient of variation (CV) obtained for the traits of L*, a* and b* values, absorption (Abs), normal grains (Ng), cooking time (Time), mass of 100 grains (M100g) and concentrations of potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) of 17 common bean genotypes evaluated in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

	L*	a*	b*	Abs	Ng	Time	M100g	K	P	Ca	Mg	Fe	Cu
				%		min:s	g	g mg^{-1} dry mater				mg mg^{-1} dry mater	
Experiment I													
Min	20.52	0.91	0.14	42.80	63.98	17:59	16.00	7.42	2.40	0.93	2.35	46.50	8.20
Max	57.68	7.61	18.51	100.00	100.00	27:14	33.50	12.25	5.62	2.03	3.38	104.70	15.00
SD	15.86	2.51	7.73	0.88	0.47	02:03	3.94	0.86	0.56	0.29	0.21	11.59	1.24
CV	41.36	67.32	88.29	9.22	4.79	09.36	16.55	8.36	16.18	18.96	7.36	17.03	11.47
Experiment II													
Min	20.23	0.94	0.47	13.71	28.02	10:44	18.70	8.47	1.48	1.01	2.18	45.10	7.40
Max	60.00	5.96	19.48	100.00	100.00	25:59	40.50	12.04	3.97	2.48	3.49	95.30	12.00
SD	17.59	1.70	8.23	1.38	0.89	02:38	4.46	0.74	0.44	0.28	0.24	12.64	1.14
CV	44.27	55.92	85.52	14.52	9.21	18.41	18.97	7.36	15.87	18.14	7.73	20.03	11.67
Experiment III													
Min	20.69	0.68	0.35	59.25	71.92	13:09	20.10	8.19	1.88	1.28	1.28	42.30	1.30
Max	62.11	8.67	21.42	100.00	100.00	27:02	31.40	13.86	4.50	3.00	1.91	68.50	6.60
SD	17.92	2.58	8.56	0.82	0.41	03:18	2.92	0.90	0.84	0.43	0.11	5.39	1.31
CV	44.60	72.86	87.05	8.17	4.14	18.00	11.60	8.08	28.28	20.80	6.43	9.59	36.77
Experiment IV													
Min	20.21	0.72	0.47	60.65	95.93	09:09	26.00	8.19	1.89	0.50	1.13	35.80	4.60
Max	62.44	5.28	17.12	92.82	100.00	15:30	37.90	14.07	5.97	2.23	1.81	69.00	8.80
SD	18.23	1.73	6.99	0.36	0.03	01:32	2.84	1.12	0.79	0.36	0.13	6.50	0.97
CV	45.45	65.18	86.34	4.13	0.28	12.27	9.26	10.40	24.18	37.27	8.86	14.04	16.19
Experiments I and II													
Min	20.23	0.91	0.14	13.71	28.02	10:44	16.00	7.42	1.48	0.93	2.18	45.10	7.40
Max	60.00	7.61	19.48	100.00	100.00	27:14	40.50	12.25	5.62	2.48	3.49	104.70	15.00
SD	16.68	2.16	7.95	1.15	0.72	04:29	4.19	0.81	0.61	0.29	0.24	12.33	1.29
CV	42.72	63.87	86.58	12.10	7.32	24.71	17.71	7.98	19.45	18.47	8.06	18.79	12.54
Experiments I, II and III													
Min	20.23	0.68	0.14	13.71	28.02	10:44	16.00	7.42	1.48	0.93	1.28	42.30	1.30
Max	62.11	8.67	21.42	100.00	100.00	27:14	40.50	13.86	5.62	3.00	3.49	104.70	15.00
SD	17.05	2.30	8.14	1.08	0.63	04:07	3.87	0.95	0.70	0.43	0.65	11.41	3.42
CV	43.26	66.98	86.56	11.15	6.42	22.61	16.02	9.02	22.61	24.64	25.34	18.27	42.57
Experiments I, II, III and IV													
Min	20.21	0.68	0.14	13.71	28.02	09:09	16.00	7.42	1.48	0.50	1.13	35.80	1.30
Max	62.44	8.67	21.42	100.00	100.00	27:14	40.50	14.07	5.97	3.00	3.49	104.70	15.00
SD	17.31	2.19	7.87	1.03	0.55	04:24	4.61	1.00	0.72	0.53	0.74	12.54	3.13
CV	43.72	67.74	86.72	10.93	5.61	26.21	17.86	9.44	23.12	34.49	32.10	21.47	41.52

and year (Table 2). Therefore, the selection of superior common bean lines for these traits should not be carried out based on data from individual experiments, since the selection of superior lines will be specific to each environment. In this case, the environmental variability between seasons and years in the same growing location must be considered so that the selection of mineral-biofortified common bean lines of high grain quality is efficient and representative of the genetic diversity of the germplasm.

Potassium concentration was the only trait that did not exhibit a significant genotype × experiment interaction effect in the different combined analyses of variance (Table 1): thus, it was not included in the selection index analyses. Previous studies have also demonstrated that the potassium concentration in common bean lines has not changed according to the growing environment (Maziero et al., 2015). In the present study, one or more common bean lines with high potassium concentration can be selected for all experiments.

Multicollinearity diagnostics were applied with the other 12 traits, and severe collinearity (CN = 5,698.1) was observed as defined by the classes proposed by Montgomery et al. (2012). To achieve weak collinearity, excluding three traits, namely, normal grains and a* and b* values, was necessary. This allowed for proper interpretation of the results of selection index analyses, preventing multicollinear variables from being implicitly weighted with greater weight in the analyses, as recommended by Cruz and Carneiro (2006).

Selection of carioca bean lines of high grain quality and mineral concentration

When the carioca bean lines were selected based on data obtained in individual experiments (I, II, III and IV), the grain quality and mineral concentration traits showed heritability estimates from low (h^2 < 30 %) to high magnitude (h^2 > 60 %) (Table 3), considering the heritability classes presented by Soltani et al. (2016). The heritability of mineral concentration identified in common bean genotypes evaluated in a single experiment was from low to intermediate magnitude in cooked grains (Katuuramu et al., 2018) and from intermediate to high magnitude in raw grains (Jost

Table 3 – Mean of the original population (Xo), mean of selected lines (Xs), heritability (h^2), genetic gain (GG) and percentage of genetic gain (PGG) for the traits of L* value, absorption (Abs), cooking time (Time), mass of 100 grains (M100g) and concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) with simultaneous selection by the multiplicative index considering the four superior carioca bean genotypes evaluated in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

Trait	Xo	Xs	h^2 %	GG	PGG	Xo	Xs	h^2 %	GS	PGG
	Experiment I					Experiment II				
L*	53.02	53.68	87.34	0.57	1.08	56.07	56.39	89.89	0.29	0.52
Abs (%)	97.47	99.82	61.00	0.07	0.73	94.57	93.77	59.39	–0.02	–0.25
Time (min:s)	22:19	23:26	82.30	55.30	4.13	13:39	12:54	81.35	–36.55	–4.46
M100g (g)	24.46	24.60	30.19	0.04	0.17	22.87	22.87	50.47	0.00	0.00
P (g kg^{-1} dry matter)	3.41	3.40	61.39	–0.00	–0.16	2.78	2.87	0.00	0.00	0.00
Ca (g kg^{-1} dry matter)	1.50	1.62	73.67	0.08	5.58	1.55	1.63	49.34	0.04	2.69
Mg (g kg^{-1} dry matter)	2.90	3.03	57.18	0.08	2.66	3.09	3.12	0.00	0.00	0.00
Fe (mg kg^{-1} dry matter)	65.62	66.97	0.00	0.00	0.00	60.75	65.27	70.76	3.20	5.27
Cu (mg kg^{-1} dry matter)	10.30	10.77	78.87	0.37	3.57	9.57	9.60	74.24	0.02	0.23
Total gain				56.51	17.76				–33.02	4.00
	Experiment III					Experiment IV				
L*	56.76	57.69	78.38	0.73	1.28	56.99	56.02	93.60	–0.91	–1.61
Abs (%)	106.97	109.33	18.56	0.02	0.20	77.37	77.16	72.33	–0.01	–0.10
Time (min:s)	18:09	16:49	81.11	–64.55	–5.93	12:41	12:04	88.48	–32.52	–4.27
M100g (g)	25.92	25.85	73.45	–0.05	–0.22	31.98	30.90	90.31	–0.98	–3.05
P (g kg^{-1} dry matter)	3.06	2.86	64.10	–0.12	–4.06	3.25	3.21	40.85	–0.01	–0.49
Ca (g kg^{-1} dry matter)	1.97	2.20	22.32	0.05	2.61	1.00	1.24	94.80	0.22	21.75
Mg (g kg^{-1} dry matter)	1.70	1.73	27.86	0.01	0.47	1.48	1.50	53.26	0.01	0.87
Fe (mg kg^{-1} dry matter)	56.08	55.88	91.28	–0.18	–0.33	47.58	51.98	77.06	3.39	7.12
Cu (mg kg^{-1} dry matter)	3.63	4.31	88.75	0.61	16.75	5.61	5.61	0.00	0.00	0.00
Total gain				–63.49	10.77				–30.82	20.22
	Experiments I and II					Experiments I, II and III				
L*	54.55	55.89	80.35	1.08	1.98	55.28	56.18	86.76	0.77	1.40
Abs (%)	96.01	99.13	0.00	0.00	0.00	99.60	101.39	0.00	0.00	0.00
Time (min:s)	17:59	18:18	0.00	0.00	0.00	18:02	17:53	19.04	–1.76	–0.16
M100g (g)	23.67	22.82	41.64	–0.35	–1.50	24.42	24.18	68.77	–0.16	–0.67
P (g kg^{-1} dry matter)	3.09	3.08	0.00	0.00	0.00	3.08	3.22	37.75	0.05	1.75
Ca (g kg^{-1} dry matter)	1.53	1.58	54.87	0.03	1.91	1.68	1.65	12.69	0.00	–0.17
Mg (g kg^{-1} dry matter)	2.99	3.04	12.41	0.00	0.17	2.56	2.57	19.79	0.00	0.01
Fe (mg kg^{-1} dry matter)	63.18	66.11	26.68	0.78	1.24	60.82	61.06	2.33	0.00	0.01
Cu (mg kg^{-1} dry matter)	9.93	9.96	73.12	0.02	0.20	7.83	8.14	0.00	0.00	0.00
Total gain				1.56	4.00				–1.10	2.17
	Experiments I, II, III and IV									
L*	55.71	56.42	89.20	0.63	1.14					
Abs (%)	93.78	94.78	0.00	0.00	0.00					
Time (min:s)	16:42	16:38	22.37	–0.80	–0.08					
M100g (g)	26.31	26.41	79.32	0.08	0.30					
P (g kg^{-1} dry matter)	3.12	2.96	53.73	–0.09	–2.83					
Ca (g kg^{-1} dry matter)	1.51	1.59	46.95	0.04	2.65					
Mg (g kg^{-1} dry matter)	2.29	2.33	50.91	0.02	0.88					
Fe (mg kg^{-1} dry matter)	57.51	57.95	23.49	0.10	0.18					
Cu (mg kg^{-1} dry matter)	7.28	7.53	0.00	0.00	0.00					
Total gain				–0.01	2.24					

et al., 2012) of Andean and Mesoamerican beans, respectively. Quantitative inheritance has been reported for potassium (Poersch et al., 2011) and phosphorus (Ribeiro et al., 2011) concentrations in common bean, indicating difficulties in selection because the effects of environmental variance are expressive. These results show that heritability for the concentration of different minerals in common bean varied with the environment, i.e., the effects of growing seasons and years can affect the magnitude of this estimate. Additionally, heritability may vary with the genetic diversity of the germplasm, the number of experiments analyzed, and the method used to obtain these estimates.

The highest total genetic gain estimates were observed in individual (I, II, III and IV) and combined (I and II) experiments, characterizing overestimates for the grain quality and mineral concentration traits. Additionally, the four superior carioca bean lines for their grain quality and mineral concentration traits selected by the multiplicative index for the experiment I were different from those selected for the individual (II, III and IV) and combined (I and II) experiments (Table 4). This can be explained because these traits showed a significant genotype × experiment interaction effect (Table 1). When this happens, it is important to consider the environmental variability between growing seasons and years in the same location where the experiments were carried out to achieve greater coincidence in selecting superior common bean lines on account of their grain quality and mineral concentration.

Table 4 – Carioca bean genotypes selected by the multiplicative index for the traits of L* value, absorption (Abs), cooking time (Time), mass of 100 grains (M100g) and concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) based on evaluations carried out in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

Genotype	L*	Abs	Time	M100g	P	Ca	Mg	Fe	Cu
		%	min:s	g	g kg^{-1} dry matter			mg kg^{-1} dry matter	
Experiment I									
Pérola	51.04	103.74	22:55	27.53	3.25	1.79	3.14	61.20	10.47
BRS MG Uai	51.18	102.52	24:54	24.17	3.19	1.85	3.14	73.47	10.37
LEC 02-16	56.97	90.32	21:43	22.33	3.92	1.31	2.83	67.83	11.30
LP 09-33	55.53	102.93	24:11	24.37	3.23	1.53	3.01	65.40	10.93
Experiment II									
GEN 45-2F-293P	58.24	94.95	13:27	22.47	2.86	2.02	3.24	73.70	9.07
SM 0312	53.29	77.29	11:00	24.27	3.01	1.50	3.03	78.25	8.77
LP 09-33	58.60	96.52	13:42	23.03	2.82	1.57	3.14	56.80	9.87
CNFC 15 097	55.44	107.66	13:26	21.73	2.79	1.45	3.09	52.35	10.70
Experiment III									
Pérola	54.88	106.83	19:13	29.33	3.34	2.02	1.80	60.70	4.35
LP 09-33	58.29	97.11	15:30	24.37	2.56	2.23	1.57	59.53	4.63
LEC 01-16	59.40	118.75	13:54	24.90	3.20	2.23	1.74	57.43	2.63
BRS MG Uai	58.18	115.28	18:40	24.80	2.37	2.33	1.82	45.85	5.65
Experiment IV									
BRS MG Uai	55.41	83.41	11:51	29.20	2.36	1.82	1.59	60.10	5.33
GEN 45-2F-293P	57.58	77.65	14:17	31.13	3.22	1.39	1.49	49.53	5.40
SM 0312	51.18	72.09	11:02	32.27	4.57	0.73	1.45	49.97	5.83
LP 09-33	59.90	75.74	11:08	31.00	2.70	1.01	1.47	48.33	5.87
Experiments I and II									
GEN 45-2F-293P	55.82	95.54	16:33	21.80	3.09	1.76	3.03	69.15	9.33
LP 09-33	57.07	99.70	18:56	23.70	3.03	1.55	3.08	61.10	10.40
BRS MG Uai	53.67	98.10	19:41	23.65	2.91	1.67	3.13	70.88	9.32
LEC 02-16	57.01	103.54	18:00	22.12	3.27	1.35	2.91	63.33	10.80
Experiments I, II and III									
LEC 01-16	57.27	99.70	16:03	23.22	3.33	1.55	2.51	59.96	8.13
Pérola	53.01	97.91	19:01	27.30	3.13	1.78	2.66	59.62	7.86
LP 09-33	57.47	98.70	17:47	23.92	2.87	1.77	2.57	60.58	8.48
LEC 02-16	56.95	109.12	18:39	22.29	3.58	1.51	2.52	64.08	8.10
Experiments I, II, III and IV									
BRS MG Uai	55.23	98.30	17:28	25.33	2.64	1.87	2.42	61.93	7.40
LP 09-33	58.08	92.62	16:08	25.69	2.83	1.58	2.30	57.52	7.83
LEC 01-16	58.01	93.01	15:13	25.58	3.29	1.40	2.23	55.88	7.61
Pérola	54.37	95.15	17:44	29.04	3.09	1.54	2.39	56.50	7.29

When the carioca bean lines were selected based on data obtained in three or four experiments, more homogeneous and similar heritability and total genetic gain values for grain quality and mineral concentration traits were observed (Table 3). Arns et al. (2018) also used the multiplicative index and found heritability estimates ranging from 81.7 to 97.5 % and a total genetic gain of 5.7 % for grain quality traits in carioca bean lines evaluated in two experiments. In turn, Dias et al. (2021) observed heritability estimates from 54.3 to 80.7 % and a total genetic gain of 19.8 % for micromineral concentration and cooking time, using the rank-sum index, in carioca bean lines evaluated in nine experiments. These results show that the number of experiments considered in the selection index analyses, and the method used influenced the heritability and genetic gain estimates. This will have implications for genetic variability, which will effectively be accessed in selecting common bean lines of high grain quality and mineral concentration. These results reinforce the need to determine the minimum number of experiments to be considered in simultaneous selection, using the multiplicative index, that provides more reliable and highly repeatable genetic gain estimates. This will be decisive in increasing the efficiency of the selection of superior common bean lines in terms of grain quality and mineral concentration traits.

The use of data from one, two, three or four experiments resulted in selecting different carioca bean lines that were outstanding for their grain quality and mineral concentration traits (Table 4). The coincidence percentage of carioca bean lines selected when comparing pairs of experiments varied from 25 to 100 %, showing that the growing season, year and number of experiments used changed the result of simultaneous selection (Table 5).

However, the results obtained in multiplicative index analyses using data from three and four experiments revealed three genotypes selected in common: LP 09-33, LEC 01-16 and Pérola (Table 4), i.e., the coincidence percentage of carioca bean lines selected was 75 % (Table 5). Therefore, the use of a larger number of experiments requires greater coincidence in selecting carioca bean lines with high grain quality and mineral concentration, to provide greater selection efficiency.

In the present study, the use of data from four experiments resulted in the selection of two lines (LP 09-33 and LEC 01-16) and one cultivar (BRS MG Uai) that outperformed cultivar Pérola (control) for grain lightness (> L* value) (Table 4). Pérola is the most widely grown carioca bean cultivar in Brazil, mainly due to the high quality of its grains. The grains of lines LP 09-33 and LEC 01-16 and cultivar BRS MG Uai showed an L* value ≥ 55.0; therefore, they were lighter than Pérola and met the color pattern of carioca bean grains sought by breeding programs (Arns et al., 2018). In addition, they showed similar absorption and a shorter cooking time than those of cultivar Pérola, i.e,, they are fast-cooking

Table 5 – Coincidence percentage of four carioca and black bean genotypes selected by the multiplicative index for the traits of L* value, absorption, cooking time, mass of 100 grains and concentrations of phosphorus, calcium, magnesium, iron, and copper based on evaluations carried out in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

Experiments	Carioca bean genotypes					
	II	III	IV	I and II	I, II and III	I, II, III and IV
I	25	75	50	75	75	75
II		25	75	50	25	25
III			50	50	75	100
IV				75	25	50
I and II					50	50
I, II and III						75
Experiments	**Black bean genotypes**					
	II	III	IV	I and II	I, II and III	I, II, III and IV
I	50	50	75	75	75	75
II		25	50	75	75	75
III			75	50	50	75
IV				50	50	75
I and II					100	75
I, II and III						75

(< 25 min; Santos et al., 2016). All selected common bean genotypes have medium-sized grains (25 to 40 g; Hegay et al., 2014), a trait highly valued by the industry.

The four carioca bean genotypes selected also have high calcium (≥ 1.4 g kg^{-1} dry matter – DM) and magnesium (≥ 2.0 g kg^{-1} DM) concentrations, according to the classification proposed by Ribeiro et al. (2013) and by Ribeiro and Mezzomo (2020), respectively. The use of common bean cultivars biofortified with calcium and magnesium in the diet may have health benefits. This is because calcium plays a protective role in bone health (Li et al., 2018) and magnesium acts on the body's susceptibility to stress (Pickering et al., 2020). Cultivar BRS MG Uai also exhibited a high iron concentration (≥ 60.4 mg kg^{-1} DM; Tryphone and Nchimbi-Msolla, 2010). Identifying iron-biofortified common bean cultivars can contribute to the prevention of anemia, which is the best-known clinical manifestation of iron deficiency in the human body (Dev and Babitt, 2017).

Line LP 09-33 was selected in all tested situations: individual and combined experiments. The genetic superiority of the line LP 09-33 in terms of grain quality and mineral concentration traits must be evaluated in a more significant number of environments, including seasons, years and growing locations, to validate its grain and nutritional quality parameters.

Selection of black bean lines of high grain quality and mineral concentration

Different heritability and genetic gain estimates were observed for the grain quality and mineral concentration traits in black bean lines when data obtained in individual (I, II, III and IV) and combined (I and II; I, II and III; and I, II, III and IV) experiments were considered (Table 6). However, data from three and four experiments resulted in more homogeneous and similar heritability and genetic gain values for the same trait. This variation in magnitude and, at times, in sign, of heritability and genetic gain values was very similar to that observed for the carioca bean lines (Table 3). The grain quality and mineral concentration traits of dark-grained common bean cultivars, evaluated in three experiments, showed heritability ≥ 54.9 % and positive genetic gain (≥ 0.1 %), as was also estimated

Table 6 – Mean of the original population (Xo), mean of selected lines (Xs), heritability (h^2), genetic gain (GG) and percentage of genetic gain (PGG) for the traits of L* value, absorption (Abs), cooking time (Time), mass of 100 grains (M100g) and concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) with simultaneous selection by the multiplicative index considering the four superior black bean genotypes evaluated in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

Trait	Xo	Xs	h^2 %	GG	PGG	Xo	Xs	h^2 %	GG	PGG
	Experiment I					Experiment II				
L*	21.84	21.95	61.59	0.07	0.31	21.33	21.54	86.86	0.18	0.85
Abs (%)	81.91	80.62	97.46	–0.07	–0.76	84.30	93.70	97.27	0.48	5.25
Time (min:s)	21:30	21:32	74.23	1.73	0.13	15:07	14:17	89.09	–44.51	–4.91
M100g (g)	23.11	24.86	82.86	1.45	6.28	24.19	27.72	97.92	3.46	14.29
P (g kg^{-1} dry matter)	3.54	3.64	17.94	0.02	0.51	2.80	2.90	15.70	0.02	0.58
Ca (g kg^{-1} dry matter)	1.58	1.67	0.00	0.00	0.00	1.58	1.60	29.91	0.01	0.48
Mg (g kg^{-1} dry matter)	2.94	2.94	73.50	–0.00	–0.16	3.09	3.08	78.18	–0.00	–0.19
Fe (mg kg^{-1} dry matter)	70.86	76.16	62.23	3.29	4.65	65.71	69.10	42.65	1.45	2.20
Cu (mg kg^{-1} dry matter)	11.32	11.87	80.90	0.44	3.87	9.99	10.47	73.34	0.35	3.49
Total gain				6.93	14.83				–38.57	22.04
	Experiment III					Experiment IV				
L*	21.50	21.62	0.00	0.00	0.00	21.10	20.96	0.00	0.00	0.00
Abs (%)	93.13	98.78	86.19	0.25	2.56	74.79	74.65	12.06	–0.00	–0.01
Time (min:s)	18:36	18:24	22.24	–2.58	–0.23	12:20	11:42	77.11	–29.01	–3.92
M100g (g)	24.34	24.11	80.56	–0.18	–0.76	29.24	30.24	79.87	0.80	2.73
P (g kg^{-1} dry matter)	2.91	3.25	79.75	0.27	9.48	3.27	3.50	54.91	0.12	3.78
Ca (g kg^{-1} dry matter)	2.23	2.48	80.24	0.20	8.98	0.90	1.05	76.52	0.11	12.79
Mg (g kg^{-1} dry matter)	1.70	1.71	0.00	0.00	0.00	1.49	1.50	67.37	0.01	0.43
Fe (mg kg^{-1} dry matter)	56.36	57.02	9.69	0.06	0.11	44.78	45.49	24.91	0.18	0.39
Cu (mg kg^{-1} dry matter)	3.51	3.74	55.70	0.13	3.70	6.47	6.92	70.97	0.32	4.93
Total gain				–1.84	23.84				–27.47	21.12
	Experiments I and II					Experiments I, II and III				
L*	21.59	21.96	32.96	0.12	0.58	21.56	21.84	40.08	0.11	0.53
Abs (%)	83.10	87.83	43.18	0.11	1.20	86.38	90.79	47.65	0.11	1.19
Time (min:s)	18:18	17:39	0.00	0.00	0.00	18:24	18:07	0.00	0.00	0.00
M100g (g)	23.65	25.16	75.69	1.15	4.85	23.88	25.23	81.12	1.10	4.60
P (g kg^{-1} dry matter)	3.17	3.29	0.00	0.00	0.00	3.08	3.06	0.00	0.00	0.00
Ca (g kg^{-1} dry matter)	1.58	1.60	24.10	0.01	0.38	1.80	1.84	57.44	0.02	1.42
Mg (g kg^{-1} dry matter)	3.02	3.03	22.10	0.00	0.08	2.58	2.58	5.96	–0.00	0.00
Fe (mg kg^{-1} dry matter)	68.28	71.63	0.00	0.00	0.00	64.31	66.32	0.00	0.00	0.00
Cu (mg kg^{-1} dry matter)	10.66	11.26	49.32	0.29	2.78	8.27	8.80	24.06	0.12	1.52
Total gain				1.69	9.87				1.47	9.26
	Experiments I, II, III and IV									
L*	21.44	21.70	38.65	0.10	0.46					
Abs (%)	83.41	88.85	47.70	0.14	1.52					
Time (min:s)	16:53	16:50	0.00	0.00	0.00					
M100g (g)	25.22	26.86	86.71	1.42	5.63					
P (g kg^{-1} dry matter)	3.13	3.17	0.00	0.00	0.00					
Ca (g kg^{-1} dry matter)	1.57	1.63	60.03	0.03	2.24					
Mg (g kg^{-1} dry matter)	2.30	2.29	0.00	0.00	0.00					
Fe (mg kg^{-1} dry matter)	59.43	60.22	0.62	0.00	0.01					
Cu (mg kg^{-1} dry matter)	7.82	8.08	53.81	0.14	1.76					
Total gain				1.83	11.62					

by the multiplicative index (Ribeiro et al., 2021). High heritability values (≥ 60 %; Soltani et al., 2016) are related to greater genetic variability and provide greater gains with selection.

Data obtained in two, three or four experiments showed total genetic gain ranging from 9.2 to 11.6 %, which are lower values than those observed in each of the four experiments analyzed individually (Table 6). The total genetic gain estimates in individual experiments (I, II, III and IV) may be inflated, as they do not consider the effects of environmental variability. Most of the traits evaluated in the present study showed a significant genotype × environment interaction effect (Table 1), i.e, the genotypes exhibited variation in grain quality and mineral concentration in the four experiments (Table 2). Therefore, obtaining genetic gain estimates with data from two or more experiments allows for greater efficiency in selecting common bean lines of high grain quality and mineral concentration.

The four black bean lines selected in experiment I were different from those selected for experiments II, III and IV (Table 7). Of the black bean lines selected, only line CHP 04-239-52 exhibited superior grain quality and mineral concentration traits in all the individual and combined experiments.

However, when the selection was undertaken based on data obtained from two, three or four experiments, three lines were identified (CHP 04-239-52, TB 02-19 and TB 03-11) as having grain quality and

Table 7 – Black bean genotypes selected by the multiplicative index for the traits of L* value, absorption (Abs), cooking time (Time), mass of 100 grains (M100g) and concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) based on evaluations carried out in the 2016 rainy (I), 2017 dry (II), 2017 rainy (III) and 2018 dry (IV) seasons and in combined experiments I and II; I, II and III; and I, II, III and IV.

Genotypes	L*	Abs	Time	M100g	P	Ca	Mg	Fe	Cu
		%	min:s	g	——— g kg^{-1} dry matter ———			—— mg kg^{-1} dry matter ——	
					Experiment I				
CHP 01-182-48	21.00	92.82	21:51	20.47	4.20	1.76	3.22	80.13	13.50
CHP 04-239-52	21.92	92.82	19:02	24.37	3.67	1.78	2.93	75.80	11.70
TB 02-19	22.89	47.80	21:40	29.00	3.29	1.44	2.84	88.33	11.53
IAC Netuno	21.99	94.76	23:35	25.60	3.43	1.71	2.77	60.37	10.73
					Experiment II				
TB 03-11	20.40	100.50	12:30	22.23	2.78	1.87	3.25	75.00	11.07
TB 02-19	23.19	102.93	17:00	39.10	3.30	1.35	2.64	70.03	11.30
LP 11-117	21.21	85.62	14:43	26.83	2.69	1.63	3.28	69.07	9.43
CHP 04-239-52	21.36	86.36	12:56	22.73	2.84	1.58	3.16	62.30	10.07
					Experiment III				
TB 03-11	21.41	105.80	20:13	23.40	3.33	2.36	1.71	59.10	5.00
Guapo Brilhante	21.51	87.67	16:14	21.80	3.93	2.51	1.74	58.43	3.50
CHP 04-239-52	22.09	101.71	17:56	25.97	2.65	2.59	1.67	56.50	3.60
IAC Netuno	21.45	100.30	19:12	25.27	3.11	2.45	1.73	54.07	2.87
					Experiment IV				
TB 02-19	21.38	81.95	10:54	34.47	3.40	0.89	1.77	49.83	8.37
IAC Netuno	20.59	72.94	13:51	27.70	3.92	1.51	1.50	48.07	6.20
Guapo Brilhante	20.72	68.06	09:45	27.97	3.65	0.88	1.39	42.07	6.60
CHP 04-239-52	21.15	76.06	12:20	30.83	3.02	0.92	1.35	42.00	6.50
					Experiments I and II				
CHP 04-239-52	21.64	89.56	15:59	23.55	3.26	1.68	3.04	69.05	10.88
CHP 01-182-48	21.32	90.13	18:19	20.93	3.45	1.67	3.23	67.60	11.90
TB 03-11	21.86	100.10	17:00	22.13	3.15	1.68	3.11	70.68	10.83
TB 02-19	23.04	72.77	19:20	34.05	3.30	1.40	2.74	79.18	11.42
					Experiments I, II and III				
CHP 04-239-52	21.79	93.59	16:38	24.36	3.05	1.98	2.59	64.87	8.46
TB 03-11	21.71	101.91	18:04	22.55	3.21	1.91	2.64	66.82	8.89
CHP 01-182-48	21.31	91.28	18:04	21.60	3.01	1.96	2.70	62.45	8.80
TB 02-19	22.57	77.29	19:40	32.42	2.98	1.52	2.38	71.13	9.04
					Experiments I, II, III and IV				
TB 02-19	22.27	78.53	17:29	32.93	3.09	1.36	2.23	65.81	8.88
CHP 04-239-52	21.63	88.99	15:34	25.98	3.04	1.72	2.28	59.15	7.97
TB 03-11	21.56	94.37	16:51	23.89	3.26	1.61	2.37	61.59	8.31
IAC Netuno	21.32	93.98	17:28	24.63	3.28	1.84	2.31	54.33	7.17

mineral concentration traits favorable to the objectives of the selection. Thus, the coincidence percentage of black bean lines selected by the multiplicative index was 75 %, or 100 % when data from two, three and four experiments (Table 5) were considered. This contributed to increasing the efficiency in selecting superior black bean lines with high grain quality and mineral concentration, confirming the results observed in the selection of carioca bean lines (Table 4).

All selected black bean lines showed high concentrations of calcium (≥ 1.4 g kg^{-1} DM; Ribeiro et al., 2013), magnesium (≥ 2.0 g kg^{-1} DM; Ribeiro and Mezzomo, 2020) and iron (≥ 60.4 mg kg^{-1} DM; Tryphone and Nchimbi-Msolla, 2010) when the selection was based on data obtained from two and three experiments (Table 7). However, this result differed when the selection was based on data from four experiments. As these traits exhibited a significant genotype × environment interaction effect (Table 1), selection based on data from four experiments may result in a more assertive selection of superior common bean lines for grain quality and mineral concentration when compared to the selection made with data from one, two and three experiments. For traits of grain quality and mineral concentration, no definition was found in terms of the necessary number of experiments to be used in the simultaneous selection of superior common bean genotypes. The results obtained in the present study did not allow for defining the number of experiments which has high repeatability in the simultaneous selection of carioca and black bean lines for grain quality and mineral concentration traits. Studies with a greater number of experiments should fill this gap.

Simultaneous selection using the multiplicative index for grain quality and mineral concentration traits in black bean lines, namely evaluated in four experiments allows a more efficiency in selecting superior common bean lines in this study. This strategy selected four outstanding black bean lines, namely, TB 02-19, CHP 04-239-52, TB 03-11 and IAC Netuno (Table 7). Except for TB 02-19, all selected lines exhibited an L* value ≤ 22.0, which is the standard sought by breeding programs for black bean cultivars (Ribeiro et al., 2003). Line TB 02-19 has lighter grains (> L* value), i.e., it has a purplish color, which may result in lower market acceptance.

As regards the other grain quality traits, lines TB 02-19 and CHP 04-239-52 have medium (25 to 40 g) grains and lines TB 03-11 and IAC Netuno have small (< 25 g) grains, and black bean consumers accept these grain sizes in Brazil. All selected lines showed high absorption and short cooking time (≤ 17 min and 29 s). Fast-cooking common bean lines (< 25 min; Santos et al., 2016) are promising for release as new cultivars, as they meet market demand.

The four selected black bean lines also exhibited a high magnesium concentration; however, only lines CHP 04-239-52, TB 03-11 and IAC Netuno showed a high calcium concentration and only lines TB 02-19 and TB 03-11 have a high iron concentration. Identifying common bean lines biofortified with one or more minerals can meet different nutritional requirements of consumers. The benefits of a diet rich in calcium, magnesium and iron are relevant to health when we consider that low intake or malabsorption of these minerals is related to several diseases (Dev and Babitt, 2017; Li et al., 2018; Pickering et al., 2020). Additionally, common bean contains polyphenols such as tannins that inhibit iron absorption in addition to phytate (Hotz and McClafferty, 2007). Consequently, the iron concentration in black beans does not always equal the amount of iron that the body can absorb (Tako et al., 2014). For this reason, further in-depth knowledge is necessary about iron bioavailability for the common bean biofortification program.

The present study demonstrated that the grain quality and mineral concentration traits in carioca and black beans were significantly affected by the genotype × environment interaction (Tables 1 and 2). As a result, heritability and genetic gain estimates varied when data obtained from individual (I, II, III and IV) and combined (I and II; I, II and III; and I, II, III and IV) experiments were considered (Tables 3 and 6). Genetic gain may be inflated based on one or two sets of experimental data. Therefore, the simultaneous selection of superior common bean lines based on data obtained from only a few experiments may be unrepresentative of the genetic variability that can effectively be exploited in breeding programs (Tables 4 and 7). Therefore, a minimum of four experiments is appropriate to provide greater efficiency and coincidence in simultaneous selection for grain quality and mineral concentration traits in carioca and black beans.

Conclusions

Grain quality and mineral concentration traits are significantly affected by the genotype × environment interaction, with the exception of potassium concentration. Heritability and genetic gain estimates for grain quality and mineral concentration traits vary when data obtained in one or more experiments are considered. Carioca (BRS MG Uai, LP 09-33, LEC 01-16 and Pérola) and black (TB 02-19, CHP 04-239-52, TB 03-11 and IAC Netuno) bean genotypes have high grain quality and mineral concentration, based on data from four experiments. Data from at least four experiments should be used to select superior common bean lines for grain quality and mineral concentration traits which will increase the efficiency of simultaneous selection.

Acknowledgments

To the National Council for Scientific and Technological Development (CNPq) for financial support and scholarships (process number 302167/2019-6).

Authors' Contributions

Conceptualization: Ribeiro, N.D. **Data acquisition:** Ribeiro, N.D. **Data analysis:** Maziero, S.M. **Design of methodology:** Ribeiro, N.D.; Maziero, S.M. **Writing and editing:** Ribeiro, N.D.

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