Revista Ciência Agronômica, v. 54, e20218523, 2023
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Indirect selection for culinary quality and minerals in beans based on genotype × environment interaction[1]

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ABSTRACT - The determination of the number of experiments required to achieve high coincidence in identifying significant correlations between culinary quality traits and/or mineral concentrations is unprecedented for common bean. The objectives of this study were to evaluate correlations between culinary quality traits and minerals in common bean lines considering data from individual and combined experiments; define the minimum number of experiments that provide high coincidence in identifying significant correlations; and identify promising traits for indirect selection. For this, seven traits related to culinary quality and the concentration of six minerals in grains of 17 common bean genotypes were evaluated. Pearson's linear correlation analysis was performed on data obtained from four individual experiments and six combinations of experiments. Twelve of the 13 evaluated traits showed a significant genotype × environment interaction effect, indicating that the common bean genotypes exhibited differences in culinary quality and mineral concentration when these were determined in different experiments. Pearson's linear correlation coefficients vary in significance, sign, and/or magnitude for the traits analyzed in individual and combined experiments. The use of data from three experiments provides a high coincidence percentage in identifying significant correlations in Pearson's linear correlation analysis. Common bean lines with high culinary quality and greater mineral concentration can be indirectly selected based on higher L* values (grain lightness) and higher calcium concentrations.

Key words: *Phaseolus vulgaris* L. Genotype × environment interaction. Pearson's linear correlation. Grain quality traits.

DOI: 10.5935/1806-6690.20230044
Editor-in-Chief: Eng. Agrônomo - Manoel Barbosa Filho - manoel.filho@ufc.br

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Received for publication 04/07/2022; approved on 23/01/2023

[1] This work was carried out with financial support from National Council for Scientific and Technological and Development (CNPq)

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INTRODUCTION

The breeding of common bean (*Phaseolus vulgaris* L.) for traits related to culinary quality—namely, color, cooking time, and grain size—and mineral concentration meets the demand of consumers who analyze the quality of grains in their purchases. For this reason, common bean breeding programs have started to put efforts into the development of new cultivars with high culinary quality and greater mineral concentrations.

Wide genetic variability has been described for color (CANCI *et al*., 2019; PARMAR *et al*., 2017), cooking time (GARCIA *et al*., 2012; PERINA *et al*., 2014; RIVERA *et al*., 2016), and mineral concentration (DELFINI *et al*., 2020; GOUVEIA *et al*., 2014; KATUURAMU *et al*., 2018; McCLEAN *et al*., 2017; SILVA *et al*., 2012; YEKEN *et al*., 2019) in grains of common bean genotypes. However, when common bean genotypes were evaluated in different experiments, culinary quality traits and/or mineral concentration showed a significant genotype × environment interaction effect (HOSSAIN *et al*., 2013; RIBEIRO *et al*., 2021a; STECKLING *et al*., 2017). These results indicate that common bean genotypes grown in different environments (growing years, seasons, and/or locations) may exhibit variations in culinary quality traits and minerals. As a consequence, promising traits for indirect selection for culinary quality and minerals must differ between growing environments, which makes the selection of superior common bean lines difficult.

Previous studies have shown that there is a correlation between culinary quality traits and/or minerals evaluated in common bean genotypes in experiments carried out in one (CANCI *et al*., 2019; PARMAR *et al*., 2017; SILVA *et al*., 2012), two (KATUURAMU *et al*., 2018; RIBEIRO *et al*., 2021b), three (HOSSAIN *et al*., 2013; McCLEAN *et al*., 2017; RIBEIRO *et al*., 2021a), or four (DELFINI *et al*., 2020) environments. Nonetheless, no study was found in the literature indicating the number of experiments that provide high coincidence in identifying significant correlations between culinary quality traits and/or minerals in common bean lines. The hypothesis is that correlations between these traits have low coincidence when based on data obtained in one or two experiments. Thus, defining the minimum number of experiments that must be used in Pearson's linear correlation analysis will provide the breeding program with greater efficiency in indirect selection for culinary quality traits and minerals in common bean lines.

Therefore, the objectives of this study were: (1) to evaluate the correlations between traits related to culinary quality and minerals in common lines based on data from individual and combined experiments; (2) define the minimum number of experiments that provide high coincidence in identifying significant correlations in Pearson's linear correlation analysis; and (3) identify promising traits for indirect selection for culinary quality and minerals.

MATERIAL AND METHODS

Description of experiments

The experiments were carried out in four growing seasons: 2016 rainy season (I), 2017 dry season (II), 2017 rainy season (III), and 2018 dry season (IV) at the campus of the Federal University of Santa Maria, located in Santa Maria, Rio Grande do Sul (RS), Brazil (29º42' S latitude, 53º49'W longitude, and 95 m altitude). The rainy-season crops were implemented between October and January and the dry-season crops from February to May, in agreement with the agricultural zoning of climatic risk for the common bean crop in RS.

The region has a humid subtropical climate and the soil is classified as a typic alitic Argisol (Hapludalf). All experiments were carried out using the conventional cultivation system (two plowing operations and one harrowing) and the field area was maintained with the cultivation of black oat from June to September.

A randomized-block experimental design with three replicates was adopted. Each experimental unit consisted of four 4-m rows spaced 0.5 m apart, with the two central rows forming the usable plot area (4 m^2). The treatments corresponded to 17 common bean genotypes: 11 lines (SM 0312, CNFC 15 097, LEC 02-16, GEN 45-2F-293P, LP 09-33, LEC 01-16, LP 11-117, TB 02-19, CHP 04-239-52, CHP 01-182-48, and TB 03-11) and six cultivars (BRS MG Uai, Pérola, Carioca, IAC Netuno, BRS Valente, and Guapo Brilhante). These genotypes were obtained by different research institutions that participated in the Value for Cultivation and Use (VCU) experiment of the Southern Brazilian Common Bean Network in the 2016 and 2017 biennium. All common bean genotypes originate from the Mesoamerican gene pool, have a mass of 100 grains ≤ 30 g, and produce carioca (beige seed coat with brown streaks) or black grains, representing the grain types most widely produced in Brazil.

The experiments were established so as to meet the minimum requirements necessary for the release of new common bean cultivars for cultivation in Brazil (MAPA, 2006). Management practices (fertilizer application, control of weeds and insects) were implemented uniformly and in line with those adopted for common bean growing in Southern Brazil. Harvesting was carried out at the maturity stage (R9), without using agricultural machinery. The grains were kept refrigerated (temperature of 5 ºC and 75% relative humidity) until the beginning of the culinary quality and mineral evaluations.

Culinary quality and mineral evaluations

The culinary quality of the grains was analyzed based on color (L*, a*, and b* values), cooking traits (absorption, normal grains, and cooking time), and mass of 100 grains. Grain color was determined using a portable colorimeter. The value of L* indicated lightness, that is, the variation between black and white; a* measured the amplitude between green and red; and b* quantified the shades between blue and yellow.

Cooking traits were evaluated in a sample of 25 grains that remained soaked in 50 mL of distilled water for 8 h, at room temperature (20 ± 2 ºC). Absorption was estimated by the following formula: [(weight of grains after soaking – weight of grains before soaking)/weight of grains before soaking] × 100. Normal grains were obtained by counting the number of grains that absorbed water after soaking relative to the total number of grains (normal and hard) and expressed in %. Cooking time was quantified in a Mattson cooker with 25 plungers. The beans were uniformly distributed on the perforated depressions of the rack of the device and cooked in a similar way to that described by Ribeiro *et al*. (2021a). Mass of 100 grains was determined in three random samples of 100 grains representative of the usable area, with 13% average moisture.

The concentration of six minerals (potassium, phosphorus, calcium, magnesium, iron, and copper) was analyzed in 30 g of raw beans randomly collected from the usable area. The grains were ground until a fine and homogeneous flour was obtained. A 0.5-g subsample of this flour was used for the nitric-perchloric digestion process (MIYAZAWA *et al*., 2009). Mineral concentration was quantified in an atomic absorption spectrophotometer, except for potassium, which was measured in a flame photometer, and phosphorus, which was determined in an optical emission spectrophotometer.

Statistical analyses

The data obtained in each of the four experiments were subjected to individual analysis of variance. For absorption and normal grains, the data were $\sqrt{x+0.5}$-transformed, in which x corresponds to the trait value, and cooking time was converted to s. The significance level was checked by the F test at 5% probability, and the homogeneity of residual variances was evaluated by Hartley's maximum F test.

Combined analysis of variance was performed considering all effects as random, except for the genotype effect, which was fixed. The F test at 5% probability was also used to identify significant traits. The phenotypic correlation matrix generated in combined analysis of variance was used for multicollinearity diagnostics. In this analysis, the condition number (CN) was associated with a collinearity class (weak, moderate or strong, and severe), based on the classification table by Montgomery, Peck and Vining (2012).

Pearson's linear correlation analysis was carried out with the data obtained in each of the four individual experiments: 2016 rainy season (I), 2017 dry season (II), 2017 rainy season (III), and 2018 dry season (IV); and for six combinations of experiments (I and II; I and III; II and IV; III and IV; I, II, and III; and I, II, III, and IV). For this, the phenotypic correlation matrix generated in analysis of variance of experiment I was used to undertake the correlation analysis of experiment I. The same procedure was adopted for correlation analysis of the other individual and combined experiments. The significance of correlation coefficients was analyzed by Student's t test, at 5% probability. All statistical analyses were performed in Genes software (CRUZ, 2016).

RESULTS AND DISCUSSION

Individual and combined analysis of variance

Residual variances were heterogeneous for b* value, normal grains, and iron concentration. These traits required correcting the degrees of freedom of the error and of the genotype × environment interaction, as proposed by Cruz (2016). This procedure allowed obtaining homogeneous residual variances (highest/lowest residual mean square < 7) for all traits and conducting combined analysis of variance.

Seven of the 13 evaluated traits exhibited a significant genotype effect (Table 1), indicating the existence of genetic variability for most of the culinary quality traits and minerals determined in the common bean lines and cultivars. Great genetic diversity has also been described for grain traits in common bean genotypes, namely, color (CANCI *et al*., 2019; PARMAR *et al*., 2017), cooking (RIVERA *et al*., 2016), and mineral concentration (GOUVEIA *et al*., 2014; SILVA *et al*., 2012; YEKEN *et al*., 2019). However, all traits related to culinary quality and the concentration of five minerals showed a significant genotype × environment interaction effect, similarly to what was reported for common bean genotypes evaluated in different environments (RIBEIRO *et al*., 2021a; STECKLING *et al*., 2017). These results demonstrate that common bean lines and cultivars grown in different years, seasons, and/or locations may vary in traits related to culinary quality and minerals. Thus, when a significant genotype × environment interaction effect occurs, the identification of promising traits for use in indirect selection for culinary quality and minerals is expected to be different for each growing environment.

The common bean lines and cultivars did not differ in terms of potassium concentration, that is, the genotype and genotype × environment interaction effects were not significant for this mineral. For this reason, potassium concentration values were not included in Pearson’s linear correlation analyses. In addition, severe multicollinearity was observed (CN = 5,698.14) based on the classification table by Montgomery, Peck and Vining (2012). To achieve weak collinearity (CN < 100), highly correlated traits, traits with a greater weight in the last eigenvectors, and traits showing greater variance inflation factors were excluded before Pearson’s linear correlation analysis. This prevents multicollinear variables from implicitly receiving a greater weight in Pearson’s linear correlation analysis and results in the correct interpretation of results (CRUZ; CARNEIRO, 2014). Therefore, the traits of b* and a* values and normal grains were also not included in Pearson’s linear correlation analyses.

Table 1 - Combined analysis of variance containing the degrees of freedom (DF), mean squares (MS), P value (P val.), mean, coefficient of experimental variation (CEV), and selective accuracy (SA) for the traits of L*, a* and b* values, absorption (ABS, %), normal grains (NG, %), cooking time (TIME, min:s), mass of 100 grains (M100G, g), and concentrations of potassium (K, g kg^{-1} 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), and copper (Cu, mg kg^{-1} DM) obtained in 17 common bean genotypes evaluated in four experiments carried out from 2016 to 2018

Source of variation	DF	L*		a*		b*		ABS		NG	
		MS	P val.[b]	MS	P val.	MS	P val.	MS	P val.	MS	P val.
Block/environment	8	3.85		1.42		2.93		0.18		0.04	
Genotype (G)	16	3758.06	0.000	53.32	0.000	767.49	0.000	3.83	0.015	1.71	0.012
Environment (E)	3	36.63	0.005	12.14	0.007	32.78	0.003	14.26	0.000	0.88	0.000
G x E	48	6.95	0.000	1.10	0.000	3.70	0.000	1.70	0.000	0.70	0.000
Residue	128	1.63		0.18		0.76		0.23		0.06	
Mean		39.58		3.24		9.08		88.80		96.52	
CEV (%)		3.22		13.31		9.63		5.06		2.59	
SA		1.00		0.99		1.00		0.75		0.77	

Source of variation	DF	TIME		M100G		K		P		Ca	
		MS	P val.	MS	P val.	MS	P val.	MS	P val.	MS	P val.
Block/environment	8	107314.05		10.83		1.38		1.75		0.11	
Genotype (G)	16	26128.66	1.000	80.77	0.000	1.64	0.066	0.83	0.118	0.35	0.034
Environment (E)	3	3247435.26	0.000	570.07	0.000	11.42	0.008	4.59	0.122	11.02	0.000
G x E	48	42676.88	0.000	13.79	0.000	0.93	0.079	0.53	0.009	0.17	0.000
Residue	128	8409.42		4.37		0.67		0.31		0.07	
Mean		16:47		25.80		10.57		3.13		1.54	
CEV (%)		9.10		8.10		7.76		17.80		17.47	
SA		0.00		0.91		0.66		0.60		0.70	

Source of variation	DF	Mg		Fe		Cu	
		MS	P val.	MS	P val.	MS	P val.
Block/environment	8	0.04		62.44		1.09	
Genotype (G)	16	0.04	1.000	162.12	1.000	4.09	0.090
Environment (E)	3	34.65	0.000	4552.31	0.000	570.29	0.000
G x E	48	0.05	0.001	188.47	0.008	2.47	0.000
Residue	128	0.02		98.74		0.64	
Mean		2.30		58.41		7.53	
CEV (%)		6.83		17.01		10.66	
SA		0.00		0.00		0.63	

Correlation analysis using data from individual experiments

Pearson's linear correlation coefficients varied in significance, sign, and/or magnitude for the different traits evaluated in individual experiments (Table 2). Additionally, the number of significant correlations ranged from two (experiment III) to six (experiments I, II, and IV), showing that the correlation estimates were not constant in the four experiments. Correlation estimates between culinary quality traits determined in common bean genotypes were variable (PERINA *et al*., 2014) and not significant (GARCIA *et al*., 2012) when evaluated in different growing locations and seasons. On the other hand, the obtained correlation estimates between minerals were different in experiments with common bean genotypes conducted in three locations (ZILIO; SOUZA; COELHO, 2017) and in eight combinations of growing years, seasons, and locations (DIAS *et al*., 2021). Therefore, the results of Pearson's linear correlation analysis will be specific for the common bean genotypes evaluated in the year, season, and location in which the experiment was carried out.

Table 2 - Pearson's correlation coefficients obtained between 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) obtained in 17 common bean genotypes evaluated in the experiments I (2016 rainy season), II (2017 dry season), III (2017 rainy season), and IV (2018 dry season)

	ABS	TIME	M100G	P	Ca	Mg	Fe	Cu
				Experiment I				
L*	0.47^{ns}	0.21^{ns}	0.21^{ns}	-0.14^{ns}	-0.26^{ns}	-0.19^{ns}	-0.33^{ns}	-0.43^{ns}
ABS		0.28^{ns}	0.02^{ns}	-0.12^{ns}	0.24^{ns}	0.12^{ns}	-0.58*	-0.32^{ns}
TIME			0.48*	-0.32^{ns}	0.15^{ns}	0.11^{ns}	-0.17^{ns}	-0.19^{ns}
M100G				-0.44*	0.03^{ns}	-0.32^{ns}	0.03^{ns}	-0.27^{ns}
P					-0.33^{ns}	0.04^{ns}	0.34^{ns}	0.76*
Ca						0.69*	0.06^{ns}	0.04^{ns}
Mg							0.20^{ns}	0.34^{ns}
Fe								0.65*
				Experiment II				
L*	0.23^{ns}	-0.30^{ns}	-0.14^{ns}	-0.05^{ns}	-0.07^{ns}	0.01^{ns}	-0.28^{ns}	-0.21^{ns}
ABS		-0.73*	0.12^{ns}	0.10^{ns}	0.18^{ns}	0.27^{ns}	-0.42^{ns}	0.43^{ns}
TIME			0.20^{ns}	-0.03^{ns}	-0.40^{ns}	-0.56*	0.21^{ns}	-0.13^{ns}
M100G				0.81*	-0.29^{ns}	-0.61*	0.27^{ns}	0.32^{ns}
P					-0.14^{ns}	-0.58*	0.32^{ns}	0.37^{ns}
Ca						0.72*	0.17^{ns}	-0.15^{ns}
Mg							-0.21^{ns}	-0.21^{ns}
Fe								-0.24^{ns}
				Experiment III				
L*	0.54*	-0.16^{ns}	0.30^{ns}	0.14^{ns}	-0.38^{ns}	0.04^{ns}	-0.02^{ns}	0.02^{ns}
ABS		-0.30^{ns}	-0.02^{ns}	0.04^{ns}	-0.06^{ns}	0.21^{ns}	0.07^{ns}	0.15^{ns}
TIME			0.34^{ns}	0.14^{ns}	-0.26^{ns}	0.21^{ns}	-0.07^{ns}	0.10^{ns}
M100G				-0.28^{ns}	-0.30^{ns}	-0.05^{ns}	-0.32^{ns}	0.14^{ns}
P					-0.03^{ns}	0.36^{ns}	0.68*	-0.38^{ns}
Ca						0.20^{ns}	-0.15^{ns}	0.17^{ns}
Mg							-0.03^{ns}	0.29^{ns}
Fe								-0.27^{ns}

Continuation Table 2

				Experiment IV				
L*	0.32^{ns}	0.15^{ns}	0.54*	-0.07^{ns}	0.17^{ns}	-0.08^{ns}	0.25^{ns}	-0.57*
ABS		0.27^{ns}	0.43^{ns}	-0.45^{ns}	0.26^{ns}	0.60*	0.39^{ns}	-0.04^{ns}
TIME			0.19^{ns}	-0.10^{ns}	0.15^{ns}	0.04^{ns}	0.01^{ns}	-0.50*
M100G				0.13^{ns}	-0.11^{ns}	0.33^{ns}	0.19^{ns}	-0.01^{ns}
P					-0.20^{ns}	-0.11^{ns}	-0.14^{ns}	0.18^{ns}
Ca						0.25^{ns}	0.70*	-0.17^{ns}
Mg							0.62*	0.39^{ns}
Fe								-0.13^{ns}

*Significant by the *t* test at 0.05 probability. ^{ns}Not significant

Two significant correlations were common only to experiments I and II, namely, mass of 100 grains and phosphorus concentration; and calcium concentration and magnesium concentration. Therefore, there was low coincidence between correlations that were significant when Pearson's linear correlation analysis was performed using data from individual experiments. This can be attributed to the fact that 12 of the 13 evaluated traits showed a significant genotype × environment interaction (Table 1). Thus, most of the culinary quality traits and minerals determined in common bean genotypes showed variation depending on the growing environment, and this also altered the correlations that were significant in each of the experiments (Table 2). These results confirm the hypothesis that identifying promising traits for indirect selection for culinary quality and minerals in common bean lines should consider the genotype × environment interaction effect to increase the chances of a successful selection.

Correlation analysis using data from two experiments

Most of Pearson's linear correlation coefficients varied in significance, sign, and/or magnitude for the traits evaluated in the tested combinations of two experiments (Table 3), similarly to what was observed for individual experiments (Table 2). The lowest number of significant correlations was identified when Pearson's linear correlation analysis was performed using data from experiments II and IV (one), and the highest number, using data from experiments I and III (six) (Table 3). This shows that the effect of growing years and seasons influenced the significance level of correlations between culinary quality traits and minerals. Previous studies using average data from experiments carried out in two growing years found that the cooking quality traits of common bean grains were not correlated (CICHY; WIESINGER; MENDOZA, 2015) and that correlations between minerals were predominantly of low (KATUURAMU *et al*., 2018) or high (RIBEIRO *et al*., 2021b) magnitude in common bean genotypes. Therefore, the use of average data from two experiments, involving combinations of growing years and/or seasons, may lead to errors in the identification of promising traits for indirect selection for culinary quality traits and minerals in common bean lines.

Only three significant correlations were coincident for the different combinations of two experiments tested: L* value and absorption (I and III; and III and IV); magnesium concentration and copper concentration (I and III; and III and IV); and calcium concentration and magnesium concentration (I and II; I and III; and II and IV). No significant correlation coincided for the four combinations of experiments tested. Thus, the use of average data from two experiments resulted in low coincidence in obtaining significant correlations between culinary quality traits and minerals in common bean genotypes, similarly to what was observed in the present study when data from individual experiments were considered (Table 2). These findings show that the use of data from one or two experiments in Pearson's linear correlation analysis does not allow for high coincidence in identifying significant correlations between culinary quality traits and minerals. To increase the efficiency of indirect selection for culinary quality traits and minerals in common bean lines, it is necessary to identify the minimum number of experiments to be used in Pearson's linear correlation analysis.

Correlation analysis using data from three and four experiments

Three correlations showed significance when data from three or four experiments were used. Two of these correlations were coincident in magnitude and sign, namely, L* value and absorption; and calcium concentration and magnesium concentration (Table 4). However, there was no significant correlation between calcium concentration and magnesium concentration in common bean genotypes when Pearson's linear correlation was performed with average data from three

Table 3 - Pearson's correlation coefficients obtained between 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) obtained in 17 common bean genotypes evaluated in the experiments I and II (2016 rainy and 2017 dry seasons), I and III (2016 rainy and 2017 rainy seasons), II and IV (2017 dry and 2018 dry seasons), and III and IV (2017 rainy and 2018 dry seasons)

	ABS	TIME	M100G	P	Ca	Mg	Fe	Cu
				Experiments I and II				
L*	0.40^{ns}	-0.14^{ns}	0.00^{ns}	-0.19^{ns}	-0.20^{ns}	-0.11^{ns}	-0.40^{ns}	-0.38^{ns}
ABS		-0.55*	0.04^{ns}	-0.14^{ns}	0.19^{ns}	0.26^{ns}	-0.46^{ns}	0.02^{ns}
TIME			0.14^{ns}	-0.09^{ns}	-0.19^{ns}	-0.04^{ns}	0.16^{ns}	-0.08^{ns}
M100G				-0.02^{ns}	-0.19^{ns}	-0.47^{ns}	0.29^{ns}	0.06^{ns}
P					-0.51*	-0.28^{ns}	0.25^{ns}	0.79*
Ca						0.73*	-0.02^{ns}	-0.34^{ns}
Mg							-0.19^{ns}	-0.11^{ns}
Fe								0.14^{ns}
				Experiments I and III				
L*	0.57*	0.02^{ns}	0.26^{ns}	0.05^{ns}	-0.38^{ns}	-0.14^{ns}	-0.31^{ns}	-0.34^{ns}
ABS		-0.07^{ns}	0.00^{ns}	-0.07^{ns}	0.07^{ns}	0.12^{ns}	-0.49*	-0.19^{ns}
TIME			0.45^{ns}	-0.21^{ns}	-0.13^{ns}	-0.01^{ns}	-0.13^{ns}	0.23^{ns}
M100G				-0.49*	-0.25^{ns}	-0.29^{ns}	-0.12^{ns}	0.06^{ns}
P					-0.06^{ns}	-0.02^{ns}	0.25^{ns}	-0.21^{ns}
Ca						0.66*	0.03^{ns}	0.53*
Mg							0.10^{ns}	0.54*
Fe								0.45^{ns}
				Experiments II and IV				
L*	0.27^{ns}	-0.25^{ns}	0.13^{ns}	-0.07^{ns}	0.11^{ns}	-0.03^{ns}	-0.12^{ns}	-0.43^{ns}
ABS		-0.43^{ns}	0.26^{ns}	-0.13^{ns}	0.22^{ns}	0.47^{ns}	-0.23^{ns}	0.19^{ns}
TIME			0.05^{ns}	-0.19^{ns}	-0.02^{ns}	-0.18^{ns}	-0.08^{ns}	0.00^{ns}
M100G				0.29^{ns}	-0.28^{ns}	-0.21^{ns}	0.20^{ns}	0.45^{ns}
P					-0.25^{ns}	-0.36^{ns}	0.27^{ns}	0.22^{ns}
Ca						0.60*	0.36^{ns}	-0.44^{ns}
Mg							0.08^{ns}	-0.32^{ns}
Fe								-0.14^{ns}
				Experiments III and IV				
L*	0.55*	-0.04^{ns}	0.45^{ns}	0.06^{ns}	-0.13^{ns}	-0.05^{ns}	0.28^{ns}	-0.29^{ns}
ABS		0.01^{ns}	0.23^{ns}	-0.09^{ns}	0.06^{ns}	0.22^{ns}	0.24^{ns}	0.00^{ns}
TIME			0.31^{ns}	0.14^{ns}	-0.14^{ns}	0.33^{ns}	0.08^{ns}	-0.17^{ns}
M100G				-0.12^{ns}	-0.31^{ns}	0.30^{ns}	0.07^{ns}	0.12^{ns}
P					-0.20^{ns}	-0.09^{ns}	0.26^{ns}	-0.18^{ns}
Ca						0.09^{ns}	-0.02^{ns}	0.14^{ns}
Mg							0.44^{ns}	0.55*
Fe								0.23^{ns}

*Significant by the *t* test at 0.05 probability. ^{ns}Not significant locations (HOSSAIN *et al.*, 2013; McCLEAN *et al.*, 2017). These results indicate that correlation estimates between culinary quality traits and minerals determined in common bean genotypes evaluated in different growing years and seasons may be different from those obtained in different growing locations. This can be explained by the fact that the genotype × year and genotype × season interactions are more important than the genotype × location interaction when the genotype × environment interaction is decomposed (TORGA *et al.*, 2013). The observed differences between common bean genotypes grown in different years can be attributed to climatic factors (temperature, precipitation, relative humidity, among others) and biotic factors (diseases, pests, and weeds), whereas differences between growing seasons can be explained by climatic and biotic factors and management practices. Therefore, the differences between growing years and seasons contributed to the fact that the correlation estimates between culinary quality traits and minerals of the common bean genotypes were not 100% coincident in the 10 correlation analyses tested (Tables 2, 3, and 4).

The correlation between L* value and absorption was significant in five correlation analyses, that is, it was coincident in 50% of the tested correlation analyses. Additionally, the correlation between calcium concentration and magnesium concentration was significant in seven correlation analyses, which corresponds to 70% coincidence in the tested correlation analyses. These two correlations revealed, with a high coincidence percentage (≥ 50%), that common bean lines with light grains (higher L* value) showed a higher absorption percentage and that an increase in calcium concentration will result in an increase in magnesium concentration. In this way, common bean lines with better culinary quality and higher mineral concentration can be indirectly selected based on higher L* values and higher calcium concentrations. The other correlations between culinary quality traits and minerals showed a low coincidence percentage in individual and combined experiments and, as such, are not promising for the identification of traits to be used in indirect selection.

A total of 36 correlations between pairs of culinary quality traits and minerals were evaluated;

Table 4 - Pearson's correlation coefficients obtained between 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) obtained in 17 common bean genotypes evaluated in the experiments 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)

	ABS	TIME	M100G	P	Ca	Mg	Fe	Cu
				Experiments I, II, and II				
L*	0.50*	-0.20^{ns}	0.09^{ns}	0.02^{ns}	-0.37^{ns}	-0.09^{ns}	-0.38^{ns}	-0.35^{ns}
ABS		-0.37^{ns}	0.07^{ns}	-0.20^{ns}	-0.03^{ns}	0.26^{ns}	-0.44^{ns}	-0.05^{ns}
TIME			0.27^{ns}	0.02^{ns}	-0.10^{ns}	-0.10^{ns}	0.20^{ns}	0.20^{ns}
M100G				-0.39^{ns}	-0.39^{ns}	-0.48*	0.08^{ns}	0.26^{ns}
P					-0.18^{ns}	-0.28^{ns}	0.27^{ns}	-0.04^{ns}
Ca						0.72*	-0.05^{ns}	0.07^{ns}
Mg							-0.21^{ns}	-0.06^{ns}
Fe								0.26^{ns}
				Experiments I, II, III, and IV				
L*	0.51*	-0.14^{ns}	0.20^{ns}	-0.00^{ns}	-0.19^{ns}	-0.12^{ns}	-0.26^{ns}	-0.46^{ns}
ABS		-0.06^{ns}	0.16^{ns}	-0.24^{ns}	0.08^{ns}	0.30^{ns}	-0.31^{ns}	-0.18^{ns}
TIME			0.26^{ns}	0.04^{ns}	0.04^{ns}	0.23^{ns}	0.10^{ns}	0.09^{ns}
M100G				-0.19^{ns}	-0.37^{ns}	-0.24^{ns}	0.14^{ns}	0.27^{ns}
P					-0.32^{ns}	-0.57*	0.11^{ns}	-0.07^{ns}
Ca						0.62*	0.04^{ns}	-0.07^{ns}
Mg							-0.00^{ns}	-0.06^{ns}
Fe								0.32^{ns}

*Significant by the *t* test at 0.05 probability. ^{ns}Not significant however, 33 correlations were not significant when Pearson's linear correlation analysis was performed using data from three or four experiments (Table 4). When the correlation between two traits is not significant, there are no linked genes or pleiotropic effects, i.e., the genetic values of the traits are independent (BALESTRE *et al*., 2013). Therefore, the lack of association between most of the culinary quality traits and minerals evaluated suggests ease of selection of superior common bean lines.

It was not possible to define the number of experiments that provide 100% coincidence in the identification of correlated pairs of culinary quality traits and minerals in Pearson's linear correlation analysis from the database used in this study. However, the use of data from three and four experiments resulted in 66.66% coincidence in the identification of two positive correlations: L* value and absorption (r = 0.50 and 0.51, respectively); and calcium concentration and magnesium concentration (r = 0.72 and 0.62, respectively). Experiments conducted in three (HOSSAIN *et al*., 2013; McCLEAN *et al*., 2017) or four (DELFINI *et al*., 2020) environments identified important correlations between culinary quality traits and/or minerals in common bean genotypes. Despite this, no previous study was found in the literature determining the minimum number of experiments to be used in Pearson's linear correlation analysis that allow for high coincidence in the identification of significant correlations between culinary quality traits and/or minerals in common bean lines.

In the present study, 92.31% of the culinary quality traits and mineral concentrations determined in the common bean genotypes exhibited a significant genotype × environment interaction effect (Table 1). This led to variations in the significance, sign, and/or magnitude of Pearson's linear correlation coefficients obtained in individual and combined experiments (Tables 2, 3, and 4). The use of data from three experiments resulted in 66.66% coincidence in the identification of significant correlations when compared with Pearson's linear correlation analysis applied to data from four experiments (Table 4). Therefore, it is recommended to use data from at least three experiments in Pearson's linear correlation analysis for culinary quality traits and minerals. This allows the identification of promising traits for indirect selection for culinary quality traits and minerals in common bean lines with high coincidence, which will increase the efficiency of the breeding program in the selection process.

CONCLUSIONS

1. Correlations between culinary quality traits and minerals vary in significance, magnitude, and/or sign when Pearson's linear correlation analysis is performed using data from individual and combined experiments;
2. The use of data from three experiments results in a high coincidence percentage in identifying significant correlations in Pearson's linear correlation analysis;
3. Selection for higher L* values (grain lightness) and higher calcium concentrations is recommended in the indirect selection of common bean lines with high culinary quality and greater mineral concentrations.

ACKNOWLEDGEMENTS

To the National Council for Scientific and Technological Development (CNPq) for financial support and scholarships.

REFERENCES

BALESTRE, M. *et al*. Applications of multi-trait selection in common bean using real and simulated experiments. **Euphytica**, v. 189, n. 2, p. 225-238, 2013.

CANCI, H. *et al*. Assessment of variation in seed morphological traits in *Phaseolus sp*. landraces from western Anatolia. **Banat´s Journal of Biotechnology**, v. X, n. 19, p. 75-88, 2019.

CICHY, K. A.; WIESINGER, J. A.; MENDOZA, F. A. Genetic diversity and genome-wide association analysis of cooking time in dry bean (*Phaseolus vulgaris* L.). **Theoretical and Applied Genetics**, v. 128, n. 8, p. 1555-1567, 2015.

CRUZ, C. D. Genes Software-extended and integrated with the R, Matlab and Selegen. **Acta Scientiarum. Agronomy**, v. 38, n. 4, p. 547-552, 2016.

CRUZ, C. D.; CARNEIRO, P. C. S. **Modelos biométricos aplicados ao melhoramento genético**. 3. ed. Viçosa: Editora UFV, 2014. v. 2, 668 p.

DELFINI, J. *et al*. Diversity of nutritional content in seeds of Brazilian common bean germplasm. **Plos One**, v. 28, n. 9, p. 1-13, 2020.

DIAS, P. A. S. *et al*. Effectiveness of breeding selection for grain quality in common bean. **Crop Science**, v. 61, n. 2, p. 1127-1140, 2021.

GARCIA, R. A. V. *et al*. QTL mapping for the cooking time of common beans. **Euphytica**, v. 186, n. 3, p. 779-792, 2012.

GOUVEIA, C. S. S. *et al*. Nutritional and mineral variability in 52 accessions of common bean varieties (*Phaseolus vulgaris* L.) from Madeira Island. **Agricultural Sciences**, v. 5, n. 4, p. 317-329, 2014.

HOSSAIN, K. G. *et al*. Interdependence of genotype and growing site on seed mineral compositions in common bean. **Asian Journal of Plant Sciences**, v. 12, n. 1, p. 11-20, 2013.

KATUURAMU, D. N. *et al*. Genome-wide association analysis of nutritional composition-related traits and iron bioavailability in cooked dry beans (*Phaseolus vulgaris* L.). **Molecular Breeding**, v. 38, n. 44, p. 1-18, 2018.

MAPA. Ministério da Agricultura, Pecuária e Abastecimento. Requisitos mínimos para determinação do valor de cultivo e uso de feijão (*Phaseolus vulgaris*), para a inscrição no Registro Nacional de Cultivares – RNC, anexo I. Brasília: Mapa, 2006. https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/sementes-e-mudas/publicacoes-sementes-e-mudas/INN25de23demaiode2006.pdf/view. Accessed 24 February 2022.

McCLEAN, P. E. *et al*. Phenotypic diversity for seed mineral concentration in North American dry bean germplasm of Middle American ancestry. **Crop Science**, v. 57, p. 3129-3144, 2017.

MIYAZAWA, M. *et al*. Análise química de tecido vegetal. *In*: SILVA, F. C. **Manual de análises químicas de solos, plantas e fertilizantes**. 2. ed. Brasília: Embrapa Informação Tecnológica, 2009. p. 191-233.

MONTGOMERY, D. C.; PECK, E. A.; VINING, G. G. **Introduction to linear regression analysis**. 5. ed. New York: Wiley, 2012. 672 p.

PARMAR, N. *et al*. Comparison of color, anti-nutritional factors, minerals, phenolic profile and protein digestibility between hard-to-cook and easy-to-cook grains from different kidney bean (*Phaseolus vulgaris*) accessions. **The Journal of Food Science and Technology**, v. 54, n. 4, p. 1023-1034, 2017.

PERINA, E. F. *et al*. Technological quality of common bean grains obtained in different growing seasons. **Bragantia**, v. 73, n. 1, p. 14-22, 2014.

RIBEIRO, N. D. *et al*. Genetic diversity and selection of bean landraces and cultivars based on technological and nutritional traits. **Journal of Food Composition and Analysis**, v. 96, p. 1-10, 2021a.

RIBEIRO, N. D. *et al*. Technological-nutritional quality traits and relationship to bioactive compounds in Mesoamerican and Andean beans. **Revista Caatinga**, v. 34, n. 2, p. 266-275, 2021b.

RIVERA, A. *et al*. Culinary and sensory traits diversity in the Spanish core collection of common beans (*Phaseolus vulgaris* L.). **Spanish Journal of Agricultural Research**, v. 14, n. 1, p. 1-9, 2016.

SILVA, C. A. *et al*. Chemical composition as related to seed color of common bean. **Crop Breeding and Applied Biotechnology**, v. 12, n. 2, p. 132-137, 2012.

STECKLING, S. de M. *et al*. Genetic diversity and selection of common bean lines based on technological quality and biofortification. **Genetic Molecular Research**, v. 16, n. 1, p. 1-13, 2017.

TORGA, P. P. *et al*. Interaction of common beans cultivars of the black group with years, locations and sowing seasons. **Euphytica**, v. 189, n. 2, p. 239-248, 2013.

YEKEN, M. Z. *et al*. Determination of Turkish common bean germplasm for morpho-agronomic and mineral variations for breeding perspectives in Turkey. **KSU Journal of Agriculture and Nature**, v. 22, n. 1, p. 38-50, 2019.

ZILIO, M.; SOUZA, C. A.; COELHO, C. M. M. Phenotypic diversity of nutrients and anti-nutrients in bean grains grown in different locations. **Revista Brasileira de Ciências Agrárias**, v. 12, n. 4, p. 526-534, 2017.