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Effectiveness of breeding selection for grain quality in common bean

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Abstract

The aims of this study were to investigate the genetic variability and the genotype × environment interaction for quality and yield traits in common bean (*Phaseolus vulgaris* L.), to evaluate the degree of informativeness of the evaluations of grain quality in only one environment, to estimate genetic parameters for grain quality traits, and to select lines with superior grain quality. We evaluated 81 carioca common bean lines in preliminary line trials in several environments for nutritional, technological, and commercial quality and selected the 20 superior lines, which were evaluated in validation trials in nine environments. Individual and combined ANOVAs were performed for all the traits. Correlations were estimated between Fe and Zn concentrations and yield; adaptability and phenotypic stability were analyzed; and superior genotypes were selected based on the Mulamba & Mock index. It is possible to increase the Fe, Zn, and crude protein concentrations and reduce cooking time; however, increasing crude fiber is a challenge. Preliminary evaluation of the quality traits in only one environment was effective and sufficient for selection of genotypes superior in Fe concentration, crude fiber, crude protein, and cooking time; and genetic gains can be obtained from selection for these traits. Genetic and phenotypic correlations were observed between Fe and Zn concentrations. The lines CNFC 16627, CNFC 16518, CNFC 16602, CNFC 16615, and CNFC 16520 are superior based on the selection index and are recommended for breeding for grain quality in carioca common bean.

1 | INTRODUCTION

Common bean (*Phaseolus vulgaris* L.; i.e., dry edible bean) is one of the main food crops, and it is of great importance in ensuring food security. In Brazil, annual production of dry beans is 2.6 Tg of common bean (Feijão, 2019), composed mainly of the carioca (cream-colored seed coat with brown streaks) group, which largely comes from small- and medium-sized producers. It is the main source of plant protein for the Brazilian population, especially for the lower economic class (Silva & Wander, 2013).

Since it is a food so highly consumed by the population, the nutritional, technological, and commercial quality traits of bean are important aspects that must be considered in breeding to meet the demands of the consumer market. Common bean is essentially a protein-rich food with considerable Fe

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Abbreviations: 100GW, 100-grain weight; CF, crude fiber; CP, crude protein; CT, cooking time; FeC, iron concentration; PLT, preliminary line trial; SCH, seed coat color at harvest; SCS, seed coat color after storage; SY, sieve yield; VT, validation trial; ZnC, zinc concentration and Zn concentrations, which has made this grain the target of plant breeding programs for combatting malnutrition (FAO, 2016; Izquierdo et al., 2018). The possibility of increasing the Fe and Zn concentrations in bean through plant breeding has been shown by the existence of genetic variability and correlation between these two traits. This allows gains from selection and a simultaneous increase in mineral concentration in the grain (Beebe, Gonzalez, & Rengifo, 2000; Blair et al., 2010). In addition, it is possible to aggregate these traits to good yield and other agronomic traits of interest (Di Prado et al., 2019; Martins et al., 2016; Ribeiro, Mambrin, Storck, Prigol, & Nogueira, 2013).

In addition to increasing Fe and Zn concentrations in common bean, studies indicate possibilities of increasing protein and fiber concentration, as well as reducing grain cooking time (CT), one of the main indicators of technological quality. Dietary fiber is an important nutritive component, especially in dry beans, an essential dietary staple for millions of people mostly in Latin America and Africa. Thus, the increase in fiber concentrations in dry beans will allow millions of people who might suffer from malnutrition to access a fiber-rich diet (Moghaddam et al., 2017). Furthermore, it is possible to combine grain nutritional and technological quality with grain yield and commercial quality to meet the requirements of the bean production chain. Through breeding, it is possible to develop high-yielding cultivars with grain of high nutritional value and reduced CT (Buratto & Moda-Cirino, 2017; Pontes, Melo, Pereira, Bassinello, & Melo, 2015).

In the intermediate phases of the common bean breeding program of Embrapa, preliminary line trials (PLTs) are conducted in several environments. In one of these environments, the nutritional and technological quality traits described above are evaluated, and then the lines selected are evaluated once more in the validation trial (VT) in several environments. It is known that the effects of the genotype × environment interaction are marked for most of the traits under selection in common bean breeding (Dalla Corte, Moda-Cirino, Scholz, & Destro, 2003; Pereira et al., 2013; Sozen, Karadavut, Ozcelik, Bozoglu, & Akcura, 2018). In this respect, it is important that the effectiveness of selection of genotypes for superior grain quality be compared through trials conducted in one or several environments. This information directly affects the cost and time for selection and can assist in decision making and increase efficiency in development of carioca common bean cultivars.

The aims of this study were to investigate genetic variability and the effect of the environment and of the genotype × environment interaction on nutritional, technological, and commercial quality traits, as well as grain yield; to evaluate the degree of informativeness of the evaluations of grain quality obtained in only one environment; to estimate genetic parameters for nutritional and technological quality traits; to estimate genetic, phenotypic, and environmental correlations among grain quality and grain yield traits; and to select carioca common bean lines with superior quality grain.

Core Ideas

- The study enabled the increase of Fe, Zn, and crude protein contents and reduced cooking time.
- We identified superior lines for grain quality, but increased crude fiber is still a challenge.
- Preliminary tests in one environment were effective for selecting lines superior in quality traits.
- Genetic and phenotypic correlations were observed between Fe and Zn contents.
- Common bean is one of the main food crops and has importance in ensuring food security.

2 | MATERIALS AND METHODS

2.1 | Preliminary line trials and validation trial

In the PLTs, 78 lines and three cultivars—Pérola, BRS Notável, and BRS Estilo—were evaluated in 2013. A nine-by-nine triple lattice experimental design was used, with plots consisting of two 4-m rows spaced at 0.5 m, and 12 plants per meter. The trials were set up in Brasilia, Distrito Federal; Santo Antônio de Goiás, Goiás; and Sete Lagoas, Minas Gerais, Brazil, in the winter crop season and in Ponta Grossa, Paraná, Brazil, in the rainy crop season. Grain yield was evaluated in all locations. The other traits varied according to the location. In Brasilia, all the nutritional, technological, and commercial quality traits were evaluated. In Santo Antônio de Goiás, 100-grain weight (100GW) was evaluated; and in Ponta Grossa, 100GW and sieve yield (SY) were evaluated.

Nutritional quality was evaluated by the concentrations of Fe (FeC), Zn (ZnC), crude fiber (CF), and crude protein (CP); technological quality was evaluated by CT; and commercial quality was evaluated by SY, 100GW, and grain yield. The FeC and ZnC were measured in 50 bean grains from each plot, according to Di Prado et al. (2019). For CF, 20 g of grain from each plot was used through the acid–base digestion method adapted from the AOAC (1997). The CP was determined from 50 bean grains from each plot by the micro-Kjeldahl method (AOAC, 1995), on a dry matter basis. For CT, a 25-grain sample was taken from a homogeneous sample of 100-grain samples from each plot, and the Mattson cooker method was performed, according to Ribeiro, Cargnelutti Filho, and Rosa (2007). The SY and the 100GW were measured according to Dias et al. (2020);

and grain yield was determined through weighing the grain collected in the plot after correcting moisture to 13%.

From the PLT conducted in the winter crop season in Brasilia, we selected the five best lines for each trait considering the nutritional and technological quality; these lines were called the reference lines for each trait. In addition to these five, lines were selected that had FeC, ZnC, CP, and CF higher than the mean and CT lower than the mean of the 78 lines evaluated, which met the following criteria: FeC $\geq$ 56 mg kg^{-1}, ZnC $\geq$ 41 mg kg^{-1}, CP $\geq$ 25%, CF $\geq$ 4.3%, and CT $\leq$ 32 min. As a result, 20 lines with superior values for FeC, ZnC, CP, CF, and CT were selected.

The 20 lines selected in the PLT were evaluated in the VTs in nine environments: Santo Antônio de Goiás in the 2015, 2016, and 2017 winter seasons; Goiânia in the 2016 and 2017 winter seasons and in the 2016 rainy season; and Ponta Grossa in the 2015 and 2016 rainy seasons and in the 2017 dry season. A randomized block experimental design was used with 20 lines and three control cultivars (Pérola, BRS Estilo, and BRS Notável) with three replications. Plots consisted of one 3-m row, with spacing of 0.5 m between rows. All the grain quality and yield traits assessed in the PLT were evaluated, along with seed coat color at harvest (SCH) and seed coat color after storage (SCS), according to Silva, Melo, Pereira, and Melo (2014).

2.2 | Statistical analyses

Individual ANOVAs were performed for all the grain quality and yield traits evaluated in the PLT. For FeC, ZnC, CF, CP, and CT, the following genetic and phenotypic parameters were estimated: genetic, phenotypic, and environmental variances; heritability among mean values; genotypic coefficient of variation; *b* variation index; and genetic gain, assuming the genotype effect as random (Cruz, Regazzi, & Carneiro, 2012).

For yield, 100GW, and SY, the genotype effect was considered fixed and the effect of the environments as random. In the case of 100GW and SY, ANOVA was carried out using the replications of all locations through the randomized block model. Combined analysis was carried out for yield, evaluated in the four environments.

Individual and combined ANOVAs were performed in the VTs for yield and the other grain quality traits. In the combined analyses, the genotype effect was considered fixed, and the environment effect was considered random. The adaptability and stability of the genotypes was estimated in the VTs according to Nunes, Ramalho, and Abreu (2005), in which the mean of the genotypes for each environment is standardized, obtaining the z_{ij}, and the constant 3.0 was added to this so that all the z_{ij} were positive. The mean of the z_{ij} values for a determined line is its measure of adaptability, and the coefficient of variation of the z_{ij} (CV_{zi}) for each line is the measure of its stability. Genotypes with $\mathrm{CV}_{zi} < 20\%$ are considered stable.

Pearson correlations were estimated between the mean values of the lines across all the environments of the PLT and VT, considering the performance of the 20 lines selected for the FeC, ZnC, CF, CP, and CT traits. The mean values of the genotypes in the environments for each trait evaluated in the VTs were compared by the Scott–Knott test at $\alpha = .05$.

The phenotypic, genetic, and environmental correlations were estimated among the yield, FeC, and ZnC traits prioritized in selection, obtained from plot data and the means in the environments (Cruz et al., 2012). For simultaneous selection of the traits, the Mulamba and Mock (1978) index was used, which is based on classification of the genotypes for each trait in an order favorable to breeding. The ranking for each variable was obtained, attributing an order (rank) associated with the phenotypic mean of each genotype, in increasing order of classification for FeC, ZnC, CF, CP, SY, 100GW, and yield; and decreasing order for CT, SCH, and SCS, whose lower values corresponded to the best positions. For yield, FeC, and ZnC, the weights of 4, 3, and 2 were attributed, respectively, and a weight of 1 was attributed to the other traits.

3 | RESULTS AND DISCUSSION

3.1 | Preliminary line trial

There was variability among the lines for all the traits evaluated in the PLT, except for CF (Table 1). The 20 best lines for grain nutritional and technological quality, selected in the PLT to compose the VTs, exhibited mean Fe, Zn, and protein concentrations higher than the overall mean and the mean of the controls, and a lower CT. The five best lines (reference) had a mean of 65.7 mg kg^{-1} for FeC, and the best line, CNFC 16613 (highlighted line), exhibited an increase of 14 mg kg^{-1} in relation to the mean of the controls. The values observed for FeC are within the interval reported by Martins et al. (2016), Mukamuhirwa, Tusiime, and Mukankusi (2015), and Di Prado et al. (2019), who found mean FeC values from 47 to 103.92 mg kg^{-1}. For ZnC, the reference lines had a mean value of 49.4 mg kg^{-1}, and the best performing line achieved 51 mg kg^{-1}. This value was higher than those reported by the authors cited above, who found variation in ZnC from 29.21 to 43.6 mg kg^{-1}. These results confirm the potential of the best lines for use in biofortification programs.

The CP and CF concentrations of the 20 genotypes selected were near the overall mean, showing little variability (Table 1). Nevertheless, the mean of the five reference lines for CP (26.8%) and of the highlighted line CNFC 16519 (27.3%) were notably distant from the overall mean (24.8%) and from the mean of the controls (22.8%). The mean values

TABLE 1 Summary of the individual ANOVAs and mean values regarding concentrations of Fe (FeC), zinc (ZnC), crude fiber (CF), crude protein (CP), and cooking time (CT) evaluated in 81 elite lines of common bean in the 2013 winter crop season in Brasília, Distrito Federal; and sieve yield (SY) and 100-grain weight (100GW) evaluated in elite lines of common bean in the rainy crop season in Ponta Grossa, Paraná, and the winter crop season in Santo Antônio de Goiás, Goiás, and Brasília in 2013

Source of variation	df	MS					MS			
		FeC	ZnC	CP	CF	CT	df	SY	df	100GW
		—mg kg^{-1}—		—%—		min		%		g
Replications[a]	1	14.8	15.2	0.4	0.0	50.6	4	121.2	6	359.4
Blocks/replications	16	29.2	7.6	2.1	0.7	40.5				
Genotypes	80	51.4**	25.1**	3.5**	0.4ns[†]	111.4**	80	27.5**	80	20.4**
Effective error	64	23.5	5.3	1.1	0.3	22.2	320	11.6	480	1.6
Overall mean		55.9	41.6	24.8	4.4	32.4		93.5		24.6
Mean of the 20 selected[b]		61.0	45.5	25.8	4.5	30.4		94.3		23.8
Reference mean[c]		65.7	49.4	26.8	5.0	25.4		96.0		–
Highlighted line[d]		70.8	51.0	27.3	5.4	22.6		96.5		–
Mean of controls		56.0	38.6	22.6	5.0	33.7		94.5		25.5
CV, %		8.7	5.6	4.2	12.8	14.5		3.6		5.1
SA[e]		0.74	0.89	0.83	0.48	0.90		0.76		0.96

[a] The replications of the trials in lattice were considered as blocks.

[b] Mean of the 20 lines selected for grain nutritional and technological quality.

[c] Mean of the five reference lines.

[d] Best performing line.

[e] Selective accuracy.

** Significant at the .01 probability level.

[†] ns, not significant.

of CP found are near the upper extreme obtained in the literature for carioca group genotypes, from 26.8 (Buratto et al., 2009) to 29.2% (Silva et al., 2008).

For CT, the reference lines had a mean value much lower than the mean value of the controls (Table 1). Considering the mean of the highlighted line, CNFC 16661, the mean CT decreased by 11.1 min compared with that of the controls, confirming the potential of the lines for better performance than the cultivars. According to Rodrigues, Ribeiro, Cargnelutti Filho, Trentin, and Londero (2005), values <30 min for CT are desirable. Cooking times ranging from 15.5 to 51.6 min, affected by growing and storage conditions and genotypes, have been reported in the literature (Baldoni & Santos, 2005; Carbonell, Carvalho, & Pereira, 2003; Perina et al., 2014).

For the commercial quality traits, SY and 100GW, there was genetic variability (Table 1). The mean value for SY of the selected lines, the reference lines, and the highlighted line (CNFC 16627) represents high commercial quality, since the desired value is 70% (Carbonell, Chiorato, Gonçalves, Perina, & Carvalho, 2010). For 100GW, the mean of the selected lines was lower than the overall mean and of the controls. This was expected because this trait was not considered in selection. In this context, genotypes with superior quality grains, but inferior for 100GW, were also selected.

TABLE 2 Estimates of genetic variance (σ^2_g), genotypic coefficient of variation (CV_g), *b* index obtained by the ratio between the genotypic CV and experimental CV (CVg/CVe), heritability (*hš*), and expected gains from selection (GS) of the 20 superior lines and of the five reference lines for concentrations of Fe (FeC), Zn (ZnC), and crude protein (CP) and cooking time (CT)

Variable	σ^2_g	CV_g	*b*	*hš*	GS[a]	GS[b]
					—%—	
FeC	14.0	6.7	0.77	54.35	4.9	9.2
ZnC	9.9	7.5	1.40	78.66	7.4	15.0
CP	1.2	4.5	1.10	69.56	2.6	5.9
CT	44.6	20.6	1.40	80.11	4.9	18.4

[a] Expected gain from selection of the 20 superior lines for grain nutritional and technological quality.

[b] Expected gain from selection of the reference lines.

The potential for selection of lines with high FeC, ZnC, and CP and reduced CT can be observed through the estimates of the genetic parameters (Table 2). The high estimates of heritability for FeC, ZnC, CP, and CT indicate conditions favorable to breeding, with success in selection. Different ranges for heritabilities have been reported in the literature, most of them medium to high values: from 58 to 97% for FeC, from 45 to 97% for ZnC (Buratto & Moda-Cirino, 2017;

TABLE 3 Summary of combined analysis for grain yield evaluated in the 81 common bean genotypes in the rainy crop season in Ponta Grossa (Paraná) and in the winter crop season in Santo Antônio de Goiás (Goiás), Brasília (Distrito Federal), and Sete Lagoas (Minas Gerais) in 2013

Source of variation	Grain yield	
	df	MS
		kg ha^{-1}
Genotypes (G)	80	795,257**
Environments (E)	3	115,280,559**
G × E	240	374,242**
Mean effective error	544	207,665
Overall mean		2,899.6
Mean of selected lines[a]		2,805.8
Mean of the controls		3,248.2
CV, %		15.7
SA[b]		0.86

[a]Mean of the 20 lines selected for grain nutritional and technological quality.

[b]Selective accuracy.

**Significant at the .01 probability level

Silva, Abreu, Ramalho, & Maia, 2012), from 33 to 94% for CP (Londero, Ribeiro, Jost, & Cargnelutti Filho, 2008; Silva et al., 2008; Silva et al., 2012), and from 12 to 91% for CT (Baldoni & Santos, 2005; Bertoldo, 2008).

The expected gains from selection were 4.9% for FeC and 7.45% for ZnC (Table 2), which are consistent with the literature (Martins et al., 2016; Rosa et al., 2010). Nevertheless, such gains were underestimated because genotypes selected for all traits were considered. Thus, considering only the five reference lines, the gains were 9.2% for FeC and 15% for ZnC. The CT stood out, with a gain of 18.4%, greater than that found by Martins et al. (2015), which was 8.03%.

Yield is considered a very important trait, considerably affected by the environment. For that reason, it is always evaluated in various environments to increase the efficiency of selection. There was variability in yield among the lines (Table 3). The 20 selected lines had yield (2,805.2 kg ha^{-1}) lower than the yield of the controls (3,248.2 kg ha^{-1}). This was expected because this trait was not considered in selection. Furthermore, this result may be associated with the negative correlations that may exist between grain quality traits and yield traits (Mingotte, Guarnieri, Farinelli, & Lemos, 2013; Ribeiro et al., 2014; Teixeira, Lima, Abreu, & Ramalho, 2015). However, some lines among the 20 best with high yield, such as CNFC 16630 (3,128.06 kg ha^{-1}) and CNFC 16633 (3,110.89 kg ha), were statistically equal to the cultivars Pérola, BRS Estilo, and BRS Notável, which is favorable in breeding for grain quality because it confirms that it is possible to combine grain quality and grain yield.

3.2 | Validation trial

In the VT, genetic variability was detected among the genotypes, and a significant effect of the environment and genotype × environment interaction was detected for all the traits. The results indicate that conducting trials in more environments may allow variability to be detected, even for CF, a trait affected by the environment and with low genetic variance (Table 4). The efficiency of evaluation of this trait in a single PLT may be limited for the selection of superior genotypes.

The differentiated response of the genotypes for FeC and ZnC in the environments evaluated is reported by several authors (Martins et al., 2016; Pereira et al., 2014; Teixeira et al., 2015), reinforcing some studies that show they are quantitative traits (Blair et al., 2010; Cichy, Caldas, Snapp, & Blair, 2009).

The effects of the environment and of the genotype × environment interaction for CP (Pontes et al., 2015; Silva, Melo, Melo, Bassinello, & Pereira, 2013), CF (Buratto et al., 2009; Dalla Corte et al., 2003), CT (Bertoldo, Coimbra, Barili, Vale, & Rocha, 2009; Perina et al., 2014), the appearance of the grain SCH and SCS (Alvares, Silva, Melo, Melo, & Pereira, 2016; Silva et al., 2014), yield (Pereira et al., 2009; Rocha, Moda-Cirino, Destro, Fonseca Júnior, & Prete, 2010), 100GW (Oliveira, Silva, Santos, Cancellier, & Fidelis, 2014; Pereira et al., 2012, 2013), and SY (Farinelli & Lemos, 2010) have been extensively detected for genotypes of the carioca group and other groups of grains. The genotype × environment interaction represents a challenge for breeding for grain commercial quality and indicates the difficulty of selecting lines based only on mean values of a single environment.

The correlations obtained between the mean values of the 20 lines in the PLT and in the VT can indicate if conducting the PLT in a single environment (Brasília 2013) was sufficient for an effective evaluation of grain nutritional and technological quality. For the ZnC and CP traits, correlation was not detected between the results of the PLT (−.01, $p >$ .05) and VT (.33, $p >$ .05). This suggests low efficiency of selection conducted in a single environment for these traits. Moderate and significant correlations were found for FeC (.50, $p \leq$ .05) and CF (.45, $p \leq$ .05). The highest correlation was observed for CT (.75, $p \leq$ .01), which must be carefully analyzed. Expression of this trait is notably affected by adverse drying conditions, associated with high temperature and high relative humidity during seed storage, which may compromise comparison between the trials for CT (Carbonell et al., 2003; Dalla Corte et al., 2003).

The five reference lines in the PLT for each trait and their ranking in the VT are shown in Table 5. The biggest change between PLT and VT in classification of the reference lines occurred for ZnC. Only the line CNFC 16518 was among the five best in the two types of trials, occupying the best position in the PLT and the second best in the VT (Table 5). For CF, the

TABLE 4 Summary of combined analyses for concentrations of Fe (FeC), Zn (ZnC), crude protein (CP), and crude fiber (CF), cooking time (CT), seed coat color at harvest (SCH), seed coat color after storage (SCS), 100-grain weight (100GW), sieve yield (SY), and grain yield (GY) evaluated in the 23 elite lines of common bean in various environments in 2015, 2016, and 2017[a]

Trait	MSe[b]	MSg[c]	MSexg[d]	Mean	CV	SA[e]
FeC, mg kg−1	2,518.0**	399.1**	60.37	66.4	10.7	0.93
ZnC, mg kg−1	1,747.8**	37.1**	9.5*	30.9	9.0	0.86
CP, %	384.5**	8.2**	3.2**	23.2	6.2	0.97
CF, %	3.4**	0.8**	0.3**	5.2	8.6	0.86
CT, min	720.5*	413.1**	79.7*	47.9	16.1	0.93
SCH	6.5**	5.0**	1.0**	2.9	16.6	0.90
SCS	4.8**	9.2**	0.5**	3.3	14.8	0.97
100GW, g	156.1*	27.4**	2.7**	22.4	3.6	0.95
SY, %	2,007.6**	283.6**	82.9**	85.8	6.0	0.95
GY, kg ha−1	6,302,583**	1,928,600**	483,155**	2,508.5	15.4	0.96

[a] Number of environments varied for each trait.
[b] Mean square of environments.
[c] Mean square of genotypes.
[d] Mean square of the genotype by environment interaction.
[e] Selective accuracy.
[f] Significant at 7% probability by the *F* test (*p* value = .076).
*Significant at the .05 probability level.
**Significant at the .01 probability level

classification was more consistent. The reference lines CNFC 16627 and CNFC 16645 occupied the first and second positions in the VT, respectively, and the others were from the 7th to 10th positions. For FeC and CT, three of the five reference lines were among the five best in the VT; however, the line that stood out for FeC, CNFC 16613, occupied the 14th position in the VT. The greatest consistency among the trials was found for FeC, in which the lines CNFC 16533 and CNFC 16635 maintained second and third positions in the two trials. For CP, four reference lines were among the five best in the VT.

Results show that for each trait evaluated individually, except for ZnC, and considering only the mean values of the reference lines, evaluation performed in a single environment was effective in selecting superior lines. In general, it is possible to determine at least two among the five best evaluated in the VT for the traits under selection. However, for greater reliability in selection of the best genotypes, conducting evaluations in at least two environments can attribute greater consistency to the data considering the interaction for the traits evaluated.

Based on the genotype × environment interaction observed, analysis of stability and phenotypic adaptability was carried out according to the method of Nunes (2005) for reliable selection of lines. The lines CNFC 16536, CNFC 16635, CNFC 16627, and CNFC 16602 were superior for FeC, with high adaptability and good stability ($CV_{zi} < 20$; Table 5). Among these, CNFC 16635 and CNFC 16602, which are reference lines for FeC, were the most stable.

For ZnC, the lines with the highest mean values were CNFC 16602, CNFC 16533, CNFC 16645, and CNFC 16665, associated with the best stabilities in the environments (Table 5). The lines CNFC 16602 and CNFC 16533 are reference lines for FeC, and CNFC 16665 if a reference line for ZnC, which suggests that selection of the best lines for FeC in the PLT was also effective for ZnC. Using the same method, Martins et al. (2016) were able to satisfactorily combine good mean values, high adaptability, and phenotypic stability in VTs of genotypes of different types of grain.

Considering the CF trait, CNFC 16533 and CNFC 16661 stood out with better mean values and high adaptability and stability (Table 5). The line CNFC 16533 is a reference line for FeC and was superior for ZnC, just as CNFC 16661 is a reference for CF and ZnC, which favors selection for CF and ZnC in a single genotype.

For CP, the lines CNFC 16661 and CNFC 16602 were superior, exhibiting high adaptability together with the best stabilities (Table 5). The line CNFC 16661, a reference for CP, was also superior for CF, as well as CNFC 16602 for FeC and ZnC, which favors simultaneous selection for these traits. Buratto et al. (2009) detected variation from 22.5 to 25.9% for CP in evaluations of 18 genotypes of the carioca group in trials conducted in the dry crop season in the state of Paraná, a variation near that observed for the 23 genotypes (22.09–24.21%). Variations from 17.00 to 28.27% for CP were obtained for the carioca group, which proves that the trait is variable according to the genotypes and the environments (Lemos, Oliveira, Palomino, & Silva, 2004; Ribeiro, Londero, Hoffmann Junior, Poersch, & Cargnelutti Filho, 2005).

For CT, lines CNFC 16526 and CNFC 16613 were prominent for mean value and for adaptability and stability

TABLE 5 Estimates of the parameters of stability (CV_{zi}), adaptability (Z_i), and means of the concentrations of Fe (FeC), Zn (ZnC), crude fiber (CF), and crude protein (CP) and cooking time (CT), referring to 23 genotypes of common bean evaluated in 2015, 2016, and 2017 in the rainy, dry, and winter crop seasons in Santo Antônio de Goiás (Goiás), Brasília (Distrito Federal), Goiânia (Goiás), and Ponta Grossa (Paraná). The five reference lines in the preliminary line trial are identified from 1 to 5, and their ranking for the validation trial is shown between parentheses in decreasing order for performance

	FeC			**ZnC**			**CF**			**CP**			**CT**		
Genotype	**Mean**	Z_i	CV_{zi}	**Mean**	Z_i	CV_{zi}	**Mean**	Z_i	CV_{zi}	**Mean**	Z_i	CV_{zi}	**Mean**	Z_i	CV_{zi}
	mg kg^{-1}			mg kg^{-1}			%			%			min		
CNFC 16536	73.87a	4.27	19.5	32.83a	3.89	28.3	5.41a	3.50	28.5	22.52c	2.42	30.0	50.44c	3.08	15.7
CNFC 16533	72.77$^{2(2)}$a	4.18	22.2	31.97a	3.55	18.0	5.41a	3.58	15.5	23.31b	3.07	24.6	51.22d	2.95	21.5
CNFC 16635	71.67$^{3(3)}$a	3.89	15.9	30.55$^{5(13)}$b	2.83	45.8	5.08b	2.53	30.1	22.39$^{3(20)}$c	2.36	52.7	51.78d	2.83	16.9
CNFC 16627	70.96a	3.75	19.9	31.55a	3.33	30.0	5.52$^{5(1)}$a	3.86	25.2	24.11$^{5(2)}$a	3.76	22.0	49.78c	2.70	14.9
CNFC 16602	70.72$^{4(5)}$a	3.80	12.4	32.34a	3.69	11.3	5.15b	2.82	21.1	23.92a	3.62	16.2	52.94d	2.70	12.4
CNFC 16524	68.15b	3.29	28.5	32.11a	3.61	20.7	4.95b	2.14	42.2	22.88c	2.66	27.1	43.26$^{3(4)}$b	3.97	35.3
CNFC 16518	67.78$^{5(7)}$b	3.30	21.9	32.44$^{1(2)}$a	3.72	26.9	5.26a	3.13	24.5	23.51b	3.23	22.8	43.16b	4.26	34.2
CNFC 16628	67.72b	3.25	25.2	31.75a	3.49	33.7	5.32a	3.24	24.3	24.07$^{4(3)}$a	3.71	21.5	47.76c	3.08	15.4
CNFC 16608	67.63b	3.20	26.2	29.60b	2.33	22.1	5.20b	2.87	40.4	23.26b	3.08	21.5	48.62c	3.21	35.0
CNFC 16615	66.92c	3.09	17.1	31.76a	3.43	24.2	5.05b	2.32	44.8	23.24b	3.13	44.4	51.06d	3.08	22.6
CNFC 16630	66.22c	2.89	27.2	30.50b	2.71	28.2	5.46a	3.64	28.9	23.02c	2.83	30.3	53.79d	2.73	19.9
CNFC 16645	65.94c	2.85	20.4	31.64a	3.32	16.9	5.50$^{3(2)}$a	3.92	21.3	23.48b	3.18	32.7	48.64c	2.98	24.1
CNFC 16520	65.75c	2.91	22.2	30.39b	2.77	30.0	5.22b	2.97	21.2	23.28b	3.15	31.9	47.34c	3.24	19.5
CNFC 16613	65.39$^{1(14)}$c	2.81	30.9	29.76$^{3(19)}$b	2.51	45.9	5.12b	2.59	45.9	22.69c	2.52	34.2	39.71a	4.00	18.7
CNFC 16665	65.17c	2.74	27.2	31.49$^{2(11)}$a	3.29	16.7	5.32$^{2(9)}$a	3.19	30.4	22.68c	2.47	36.0	55.70d	2.57	15.7
CNFC 16606	63.95c	2.54	37.8	29.95b	2.54	37.4	5.26$^{4(10)}$a	3.11	29.1	23.30b	3.05	35.4	52.53d	2.82	24.6
Pérola	63.92c	2.61	30.9	28.94b	2.00	37.8	5.04b	2.45	45.1	23.49b	3.17	33.6	47.47c	2.82	9.5
CNFC 16661	63.81c	2.58	15.6	31.49$^{4(10)}$a	3.35	20.7	5.34$^{1(7)}$a	3.44	17.0	24.21$^{2(1)}$a	3.87	14.1	43.56$^{1(5)}$b	3.62	23.9
CNFC 16633	63.63c	2.44	36.6	29.94b	2.52	27.6	5.35a	3.36	27.1	23.09c	2.82	33.5	46.99$^{5(7)}$c	3.23	12.6
CNFC 16526	63.55c	2.50	28.9	31.04a	3.07	26.6	5.17b	2.84	22.9	22.93c	2.75	35.5	35.90$^{2(1)}$a	4.83	18.7
CNFC 16519	63.08c	2.50	35.1	30.47b	2.78	31.2	4.98b	2.26	23.1	23.56$^{1(5)}$b	3.38	22.2	44.13$^{4(6)}$b	3.85	31.4
BRS Notável	62.23c	2.27	34.1	30.02b	2.55	35.1	5.21b	3.00	39.1	23.06c	2.91	16.3	55.77d	2.57	15.7
BRS Estilo	57.04d	1.32	52.5	28.38b	1.72	19.8	5.00b	2.28	30.4	22.09c	1.90	48.0	39.85a	4.69	39.1
Mean	66.43	–	–	30.91	–	–	5.23	–	–	23.22	–	–	47.89	–	–

Note. Mean values followed by a common letter in the column do not differ from each other by the Scott–Knott test at 5% significance.

(Table 5), reconfirming that line CNFC 16526 is a reference. Lower CTs are found in the literature, from 14.20 to 34.38 min (Oliveira, Ribeiro, Maziero, Cargnelutti Filho, & Jost, 2011; Perina et al., 2014; Rodrigues et al., 2005). Wider variability for CT has been recently shown, with some genotypes reaching over 100 min (Cichy et al., 2019), which is widely affected by the genotypes, crop season, year, and location, conditions of storage and methodology to determine CT. Environmental conditions of high temperature and high relative humidity during storage were the factors that may have most affected the CT of the lines. High values for CT were found by Bertoldo et al. (2009), who evaluated the stability and adaptability of 12 genotypes of common bean of the black bean group in different growing locations and storage periods. These authors observed variation from 37 to 52 min in the mean of the environments, with variation in the growing location alone, even without storage.

The cultivars Pérola, BRS Estilo, and BRS Notável generally had lower performance and low stability and adaptability for the traits FeC, ZnC, CF, CP, and CT. It is known that the Pérola cultivar has intermediate FeC and ZnC (Martins et al., 2016; Pereira et al., 2014). In contrast, Buratto et al. (2009) found superiority of the Pérola cultivar for CP, with a mean of 24.4%, and it associated high stability and adaptability in evaluations of 18 genotypes of the carioca group. The results indicate the possibility of selection of lines that are superior to the commercial cultivars.

The line CNFC 16615 stood out for the traits SCH and SCS, since it showed stability and had low scores for seed coat color before and after storage, which indicates that the bean grains maintained a lighter colored seed coat (Table 6). Other genotypes were prominent for these traits: NFC 16518, CNFC 16519, and the cultivar BRS Estilo, with good performance before and after storage, with mean values <3. The Pérola cultivar, however, had worse performance, with darker colored bean grains and low stability in the environments, just as observed by Ribeiro, Jost, and Cargnelutti Filho (2004). The cultivar BRS Notável had high stability for SCH but obtained the worst score and low adaptability and stability for SCS. This cultivar is recommended for family farming because it has genetic resistance to various diseases and was not selected for quality traits such as grain darkening, which are of little relevance for this market segment.

High correlation (.92, $p \leq .01$) was found among the lines for SCH and SCS, which confirms the similar performance for grain color at harvest and after storage. Other authors also observed significant correlations of high magnitude between different periods of storage for grain color in genotypes of the carioca group (Silva et al., 2008, 2014). Thus, the genotypes with the lowest scores for SCH tend to exhibit the lowest scores for SCS, which represents an advantage in early identification and selection of more stable genotypes for less grain darkening.

For yield, the lines CNFC 16608, CNFC 16520, CNFC 16635, CNFC 16633, CNFC 16526, and CNFC 16627 stood out as superior to the cultivars (Table 6). It should be emphasized that the Pérola cultivar is widely grown, with high acceptance by consumers, and is a standard for commercial quality of bean grains. Thus, higher yielding genotypes that are able to combine good grain quality traits may be able to give rise to even more competitive cultivars. The lines CNFC 16608, CNFC 16520, and CNFC 16633 were the most adapted. Regarding stability ($CV_{zi} < 20$), the lines CNFC 16608, CNFC 16635, and CNFC 16520 stood out; they also had high yield, with potential for exceeding the performance of the cultivars currently in use.

In relation to SY, all the genotypes exhibited satisfactory performance, with mean values above 70%, the standard value established by Carbonell et al. (2010). The lines CNFC 16519, CNFC 16665, CNFC 16661, CNFC 16615, CNFC 16526, and CNFC 16633 and the cultivar BRS Notável stood out for SY, with mean values higher than 89%, superior to that of the cultivars Pérola and BRS Estilo. The superiority of the Pérola cultivar for SY was reported by Farinelli and Lemos (2010) in evaluations conducted during the rainy and dry crop seasons from 2005 to 2006. These authors detected a variation in SY from 75 to 78.9% for the cultivar, which is lower than the values observed in the VTs (80%). These differences can be explained in part by variations in the size of the sieves. Of the lines cited, those that combined high SY with good adaptability and stability were CNFC 16519, CNFC 16615, CNFC 16526, CNFC 16633, and CNFC 16665, standing out from the others. There is little information regarding the stability and adaptability of genotypes of common bean for SY; thus, the results obtained can contribute to more effective selection for grain quality in carioca common bean.

Considering the 100GW trait, the genotypes Pérola and CNFC 16633 stood out with mean values of ∼25 g, the minimum desired for the carioca bean standard. The Pérola cultivar varied from 21.7 to 28.20 g in the environments evaluated. This cultivar is a standard for grain size for the carioca group, with variations observed in the literature from 23.2 to 30.10 g for 100GW and a mean of 27 g under ideal growing conditions, which confirms its superiority for the trait (Correa & Gonçalves, 2012; Farinelli & Lemos, 2010; Ramos, Lemos, & Silva, 2005). Analyzing the mean, adaptability, and stability, the Pérola cultivar excelled, followed by the lines CNFC 16633 and CNFC 16615, combining the highest mean values of 100 GW and good adaptability and stability.

In general, the genotypes that had a high mean value for the trait were also the most adapted. In addition, it was possible to combine the desired mean values and wide adaptability with good stability for all the traits, which can be observed especially in the lines that were superior to the cultivars, and this represents high potential for selection. However, of the lines that were superior for the three parameters (mean for

TABLE 6 Estimates of the parameters of stability (CV_{zi}), adaptability (Z_i), and mean values for grain yield (GY), sieve yield (SY), 100-grain weight (100GW), and seed coat color at harvest (SCH) and after storage (SCS) referring to 23 genotypes evaluated in 2016 and 2017 in the rainy, dry, and winter crop seasons in Santo Antônio de Goiás (Goiás), Goiânia (Goiás), and Ponta Grossa (Paraná)

Genotype	GY			SY			100GW			SCH			SCS		
	Mean	Z_i	CV_{zi}	Mean	Z_i	CV_{zi}	Mean	Z_i	CV_{zi}	Mean	Z_i[a]	CV_{zi}	Mean	Z_i[a]	CV_{zi}
	kg ha^{-1}			%			g								
CNFC 16608	2,955a	3.91	9.9	81d	2.10	27.2	21.9f	2.61	23.9	2.86c	2.71	9.1	2.86b	3.32	13.2
CNFC 16520	2,932a	3.87	19.7	83c	2.50	28.6	21.6f	2.44	24.8	2.25b	3.41	15.0	3.19c	2.97	9.3
CNFC 16635	2,871a	3.69	11.7	80d	1.81	35.5	22.2e	2.80	27.1	3.08c	2.66	10.1	3.62d	2.63	9.8
CNFC 16633	2,847a	3.94	26.2	90a	3.43	18.9	24.6b	4.51	17.8	3.42d	2.53	10.1	4.05e	2.36	12.1
CNFC 16526	2,835a	3.61	24.9	90a	3.85	10.8	21.1g	2.11	17.0	3.17c	2.81	22.0	3.52d	2.63	14.7
CNFC 16627	2,787a	3.52	20.3	83c	2.70	43.0	22.2e	2.78	30.2	2.83c	2.91	21.2	3.24c	3.00	14.0
CNFC 16602	2,715b	3.33	27.2	83c	2.41	43.7	22.3e	2.92	12.2	3.58d	2.41	7.1	4.10e	2.29	11.3
BRS Notável	2,633b	3.43	33.7	90a	3.69	19.1	22.6e	3.10	8.4	4.08e	2.18	3.3	4.86f	1.97	15.2
CNFC 16518	2,629b	3.25	27.5	80d	2.03	51.1	21.1g	2.04	27.5	2.33b	3.22	12.7	2.81b	3.37	10.7
CNFC 16630	2,589b	3.16	22.0	88b	3.13	20.2	21.7f	2.54	22.9	3.25c	2.56	7.2	3.71d	2.63	9.5
CNFC 16615	2,544b	2.97	32.9	90a	3.93	9.4	23.6c	3.87	17.0	1.00a	6.44	12.0	1.29a	6.98	5.0
CNFC 16665	2,503c	3.12	31.8	91a	3.81	12.0	22.3e	2.95	12.0	3.08c	2.79	19.4	3.71d	2.53	11.7
CNFC 16645	2,462c	2.94	20.9	88b	3.30	36.7	20.9g	1.99	30.0	3.00c	2.74	14.4	3.62d	2.62	15.2
CNFC 16606	2,446c	3.03	30.1	86b	3.02	33.8	22.8d	3.26	16.4	3.57d	2.41	7.1	3.57d	2.58	16.6
Pérola	2,411c	2.83	26.8	80b	2.95	19.7	25.1a	4.89	19.5	2.67c	3.33	52.8	3.38c	2.82	16.5
CNFC 16661	2,390c	2.72	31.8	91a	3.48	28.9	21.2g	2.14	24.3	3.17c	2.70	8.8	3.48d	2.70	9.8
CNFC 16524	2,387c	2.67	22.1	84c	2.80	31.0	22.0f	2.75	38.3	2.83c	2.87	10.7	3.48d	2.74	8.0
CNFC 16519	2,274c	2.43	27.0	92a	4.19	9.2	23.3d	3.63	23.9	2.00b	4.00	28.6	2.57b	3.55	11.5
CNFC 16533	2,271c	2.48	34.7	82c	2.53	36.8	21.1g	2.07	21.0	3.00c	2.61	6.4	3.33c	2.86	11.3
CNFC 16536	2,241c	2.40	23.5	81d	2.13	52.4	21.9f	2.61	22.1	3.08c	2.58	7.7	3.24c	2.98	14.6
CNFC 16613	2,231c	2.36	34.2	85c	2.69	23.7	23.9c	4.05	20.6	3.17c	2.55	9.7	3.33c	2.89	14.7
BRS Estilo	1,969d	1.81	36.0	86b	3.26	17.9	23.0d	3.42	10.1	2.00b	2.30	2.9	2.81b	3.29	10.4
CNFC 16628	1,774d	1.55	62.5	89b	3.26	20.1	23.2d	3.51	11.1	3.00c	2.65	5.9	3.24c	2.96	7.6
Mean	2,508	–	–	86	–	–	22.4	–	–	2.89	–	–	3.35	–	–

Note. Mean values followed by a common letter in the column do not differ from each other by the Scott-Knott test at 5% significance.

[a] Estimates of adaptability were obtained with the data inverted.

TABLE 7 Phenotypic (r_f), genetic (r_g), and environmental (r_a) correlation coefficients among Fe (FeC) and Zn (ZnC) concentrations and grain yield (GY) referring to the 23 genotypes evaluated in multiple environments

	FeC and ZnC			FeC and GY			ZnC and GY		
Environment/crop Season	r_f	r_g	r_a	r_f	r_g	r_a	r_f	r_g	r_a
Brasília, Distrito Federal/winter 2015	.72**	.85[a]	.40[a]	–	–	–	–	–	–
Goiânia, Goiás/winter 2016	.52*	[b]	.47[a]	.05	.29	−.23	−.03	[b]	.22
Santo Antônio de Goiás, Goiás/winter 2016	.65**	[b]	.59[a]	.14	.55	.10	.05	−.10	.24
Ponta Grossa, Paraná/rainy 2016	.32	.40	.20	.42*	.59[c]	−.13	−.01	.04	−.20
Goiânia, Goiás/rainy 2016	.62**	.86[a]	.30[c]	–	–	–	–	–	–
Ponta Grossa, Paraná/dry 2017	.67**	.74[c]	.54[a]	.46*	.55[c]	.13	.34	.48	−.01
Santo Antônio de Goiás, Goiás/winter 2017	.42*	.37	.47[a]	−.14	−.28	−.02	.21	[b]	−.27[c]
Goiânia, Goiás/winter 2017	.75**	[b]	.33[a]	–	–	–	–	–	–
Mean	.72**	.79	.51[a]	.12	.06	.29[c]	.02	−.07	.16

[a] 1% Type I error rate by the by the bootstrap resampling method (Cruz, 2006).
[b] Absence of genetic variability for FeC and ZnC.
[c] 5% Type I error rate by the bootstrap resampling method (Cruz, 2006).
*Significant at the .05 probability level.
**Significant at the .01 probability level.

the trait, adaptability, and stability coefficients) and stood out in more than one trait, only two stood out for more than two of the traits: CNFC 16602 (FeC, ZnC, and CP) and CNFC 16615 (SCH, SCS, SY, and 100GW).

Knowledge of the types of associations that exist among the traits evaluated makes it possible to evaluate the potential for success in selection of the genotypes promising for multiple traits. Considering the traits prioritized in this selection, genetic, phenotypic, and environmental correlations with yield were estimated among yield, FeC, and ZnC (Table 7). The detection of significant phenotypic and genetic correlations between FeC and ZnC indicates that the genotypes with greater FeC in the grain also tend to exhibit high ZnC and that there are genetic causes, such as pleiotropy or pathways connected to each other, for this association, which represents an advantage in simultaneous selection. Blair et al. (2010) identified a single quantitative trait locus largely responsible for the variation in FeC and ZnC in common bean of Mesoamerican origin, belonging to the same gene pool as carioca common bean.

The environmental correlations were positive and significant in the same environments in which phenotypic correlations between FeC and ZnC were detected (Table 7); thus, the variations in the environment favorably affected simultaneous increase in the concentration of the two minerals in the grain. Genetic and phenotypic correlations of low and high magnitude between FeC and ZnC in common bean have been intensively reported (Martins et al., 2016; Mukamuhirwa et al., 2015; Teixeira et al., 2015; Zilio, Souza, & Coelho, 2017), which confirms the possibilities of obtaining simultaneous gains for FeC and ZnC.

Correlations between FeC and yield and between ZnC and yield (Table 7) were not found in most of the environments. Ribeiro, Jost, Cerutti, Maziero, and Poersch (2008) and Zilio et al. (2017) also did not detect correlations between FeC and yield, which suggests that the traits have independent segregation. However, moderately negative phenotypic correlations were found between FeC and yield (Ribeiro et al., 2014) and between ZnC and yield (Ribeiro et al., 2008; Zilio et al., 2017). Contrasting results may arise, because genetic correlations that have pleiotropy or genetic linkage as a cause can vary in magnitude (Ramalho, Abreu, Santos, & Nunes, 2012).

In most of the environments evaluated, correlations between FeC or ZnC and yield were not found (Table 7), and these results are favorable because they suggest that these traits are independent, making it possible to obtain simultaneous gains for FeC, ZnC, and yield. Thus, use of the selection index emerges as a promising alternative in selection of grain quality traits in common bean, as shown by Teixeira et al. (2015) and Alvares et al. (2016).

The lines CNFC 16627, CNFC 16518, CNFC 16602, CNFC 16615, and CNFC 16520 were the five best lines classified by the Mulamba & Mock index, and of these, CNFC 16627 and CNFC 16520 also stood out for high yield (Table 6). Considering the FeC and ZnC traits prioritized in selection, the lines CNFC 16627 and CNFC 16602 stand out (Table 5); both lines were also superior for CP, and CNFC 16627 was superior for CF. Since correlation between FeC and yield and ZnC and yield were not detected (Table 7) at the level of mean values, selection was favored by the greater economic weights attributed to these traits, which confirms the effectiveness of the index.

Other data were noteworthy: in the mean of the environments, the line CNFC 16518 was superior for the traits ZnC, CF, SCH, and SCS; the line CNFC 16615 had high values for ZnC and SY and obtained the best performance for SCH and

SCS; and the line CNFC 16520 had not only high values for yield, but also for SCH. Among the controls, the Pérola cultivar obtained the best classification, in 19th position, including the highest 100GW. After that, the BRS Notável cultivar occupied the 21st position and had high values for SY; however, it had the worst response for CT, SCH, and SCS and low performance for the other traits, except for yield, for which it exceeded the other cultivars. Finally, BRS Estilo had the worst classification, with good performance for only CT, SCH, and SCS. In general, the three cultivars did not exhibit good classification by the index, which shows the superiority of the lines.

Based on the Mulamba & Mock index, it is possible to select lines for potential use as parents or cultivars for different grain quality attributes. Considering the mean, stability, and adaptability, the lines CNFC 16627 and CNFC 16602 were superior for FeC, and CNFC 16602 was superior for ZnC and CP. The line CNFC 16627 had better grain yield than the controls, and CNFC 16602 had grain yield performance similar to that of the cultivar BRS Notável, which was superior to the other controls. Thus, these lines show potential for use as cultivars or for crosses in breeding aiming at biofortified cultivars.

The line CNFC 16520 was among the highest yielding lines and had better SCH than the mean; it also had good stability and adaptability. Furthermore, it was superior to the cultivars Pérola and BRS Notável for seed coat color. This line represents high potential for use as a cultivar. Considering the mean in the environments, the line CNFC 16627 was superior for CP and CF, whereas CNFC 16615 was superior for ZnC, SY, SCH, and SCS; and CNFC 16518 obtained better results for CF, ZnC, SCH, and SCS. Thus, these three lines show potential for use as parents in breeding for grain nutritional and commercial quality.

The selection of the genotypes based on the rank sum index was consistent with the previously established condition upon considering the yield, FeC, and ZnC traits. In this respect, it was possible to select high-yielding lines in combination with high FeC and ZnC in the grain, and they can be recommended for biofortification programs. Silva, Pereira, Melo, and Melo (2018) obtained good results from the Mulamba & Mock index. They prioritized the yield, SY, and 100GW traits and the appearance of the bean grains and were able to select superior common bean lines of the carioca group for most of the traits evaluated, in terms of stability and phenotypic adaptability.

There are few studies that use indices based on stability and adaptability parameters for selection of superior genotypes. Perina, Carvalho, Chiorato, Gonçalves, and Carbonell (2010) obtained satisfactory results in evaluations involving the stability and adaptability of common bean genotypes of the carioca and black bean groups for grain moisture concentration, CP, CT, and different traits of grain technological quality. The method proved to be effective in selection of superior genotypes. However, it was more laborious than the Mulamba & Mock index by requiring more variables for conducting the analyses.

4 | CONCLUSION

There is genetic variability and the effect of environments and of the genotype × environment interaction for the traits of grain nutritional, technological, and commercial quality. It is possible to increase the concentrations of Fe and Zn and CP in the bean grains and reduce the CT. The evaluation for grain quality in preliminary trials was favorable to selection of superior genotypes for FeC, CF, CP, and CT, and it was not necessary to perform VTs, since the preliminary evaluation is carried out in at least two environments to increase the effectiveness of selection, due to genotype × environment interaction. There is genetic and phenotypic correlation between FeC and ZnC; however, correlations between FeC and yield and ZnC and yield were not detected at most environments. The five superior lines based on the selection index, considering all the traits together, were the following: CNFC 16627, CNFC 16518, CNFC 16602, CNFC 16615, and CNFC 16520. The lines selected for each trait individually by the mean and the adaptability and stability parameters were CNFC 16602 and CNFC 16627 for FeC; CNFC 16602 for ZnC and CP; CNFC 16615 and CNFC 16518 for SCH and SCS; CNFC 16520 for yield; and CNFC 16615 for SY.

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AUTHOR CONTRIBUTIONS

Polianna Alves Silva Dias: Data curation; Software; Visualization; Writing-original draft; Writing-review & editing. Danilo Valente Almeida: Data curation; Formal analysis; Investigation; Software; Visualization; Writing-original draft; Writing-review & editing. Helton Santos Pereira: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing-review & editing. Leonardo Cunha Melo: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology;

Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-review & editing

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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