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Simultaneous selection for grain quality and mineral concentration in Mesoamerican common bean under drought stress

Seleção simultânea para qualidade de grãos e concentração de minerais em feijão Mesoamericano sob estresse com seca

Henrique da Silva Argenta[1]; Nerinéia Dalfollo Ribeiro[2]*; Greice Godoy dos Santos[3]; Fabricio Fuzzer de Andrade[3]

Highlights

Mass of 100 grains decreases under drought stress conditions.
Mineral concentration remains unchanged in the common bean genotypes.
Line LEC 03-16 and cultivar IPR Urutau have high commercial grain quality.
Cultivar BRS Esteio has the highest concentration of all evaluated minerals.

Abstract

In a scenario of climate change, alterations in commercial grain quality traits and minerals are expected to occur in common bean genotypes cultivated under drought stress conditions. This study was undertaken to investigate the genetic variability of commercial grain quality traits and mineral concentration in Mesoamerican common bean genotypes cultivated under drought stress conditions, as well as to carry out simultaneous selection for multiple traits. The experiments were conducted during years with precipitation levels below the annual average due to the La Niña climate phenomenon. Twelve Mesoamerican common bean genotypes, comprising elite lines and cultivars from five breeders, were assessed for 11 commercial grain quality traits and the concentration of seven minerals. The standardized index ($\overline{Z}$ index) was applied with the aim of simultaneously selecting for multiple traits. A significant genotype effect was detected for all traits, except for magnesium concentration. Thus, genetic variability was evident for most evaluated traits, enabling the selection of genotypes featuring high commercial grain quality and increased mineral concentration. However, when cultivation is carried out under conditions of prolonged water restriction, a reduction in mass of 100 grains is observed, while mineral concentration remains unchanged in the common bean genotypes. Line LEC 03-16 possesses

[1] Student of the Master's Degree in the Postgraduate Program in Agronomy, PPGAGRO, Universidade Federal de Santa Maria, UFSM, Santa Maria, RS, Brasil. E-mail: henriqueargenta@hotmail.com

[2] Profª Drª, Department of Plant Science, UFSM, Santa Maria, RS, Brasil. E-mail: nerineia@hotmail.com

[3] Doctoral Students of the Postgraduate Program in Agronomy, PPGAGRO, UFSM, Santa Maria, RS, Brasil. E-mail: godoy.greice@gmail.com; fabriciofuzzer@yahoo.com

* Author for correspondence

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the highest number of traits associated with high commercial quality in carioca grains, as well as the highest concentrations of potassium (≥ 11.95 g kg^{-1} dry matter - DM), phosphorus (≥ 4.71 g kg^{-1} DM), zinc (29.71 mg kg^{-1} DM), and copper (8.38 mg kg^{-1} DM). Cultivar IPR Urutau has high commercial quality of black grains, whereas cultivar BRS Esteio excels for the highest concentration of potassium (≥ 11.66 g kg^{-1} DM), phosphorus (≥ 3.88 g kg^{-1} DM), calcium (≥ 0.86 g kg^{-1} DM), iron (59.62 mg kg^{-1} DM), zinc (25.17 mg kg^{-1} DM), and copper (7.72 mg kg^{-1} DM). Line LEC 03-16 and cultivar BRS Esteio exhibit greater mineral concentration under drought stress, and their cultivation is promising for food and nutritional security.
Key words: Genotype × environment interaction. *Phaseolus vulgaris* L. Simultaneous selection. $\bar{Z}$ index.

Resumo

Em um cenário de mudanças climáticas se espera que ocorram alterações em caracteres de qualidade comercial de grãos e de minerais em genótipos de feijão cultivados em condições de estresse com seca. Este estudo foi realizado para avaliar a variabilidade genética de caracteres de qualidade comercial de grãos e concentração de minerais em genótipos de feijão Mesoamericano produzidos em condições de estresse com seca e realizar a seleção simultânea para múltiplos caracteres. Os experimentos foram implementados em anos em que se registrou precipitação abaixo da média anual em decorrência do fenômeno climático La Niña. Doze genótipos de feijão Mesoamericano, incluindo linhagens elite e cultivares de cinco obtentores, foram avaliados em relação a 11 caracteres de qualidade comercial de grãos e a concentração de sete minerais. O índice padronizado (índice $\bar{Z}$) foi aplicado com o objetivo de realizar a seleção simultânea para múltiplos caracteres. Efeito de genótipo significativo foi observado para todos os caracteres, exceto para a concentração de magnésio. Portanto, houve variabilidade genética para a maioria dos caracteres avaliados e isso permite a seleção de genótipos com alta qualidade comercial de grãos e maior concentração de minerais. No entanto, quando o cultivo é realizado em condições de restrição hídrica prolongada ocorre uma diminuição na massa de 100 grãos, mas concentração de minerais não é alterada nos genótipos de feijão. A linhagem LEC 03-16 possui o maior número de caracteres que conferem alta qualidade comercial de grãos carioca e as maiores concentrações de potássio (≥ 11,95 g kg^{-1} de matéria seca – MS), fósforo (≥ 4,71 g kg^{-1} MS), zinco (29,71 mg kg^{-1} MS) e cobre (8,38 mg kg^{-1} MS). A cultivar IPR Urutau tem alta qualidade comercial de grãos preto e a cultivar BRS Esteio se destaca pela maior concentração de potássio (≥ 11,66 g kg^{-1} MS), fósforo (≥ 3,88 g kg^{-1} MS), cálcio (≥ 0,86 g kg^{-1} MS), ferro (59,62 mg kg^{-1} MS), zinco (25,17 mg kg^{-1} MS) e cobre (7,72 mg kg^{-1} MS). A linhagem LEC 03-16 e a cultivar BRS Esteio apresentam maior concentração de minerais em condições de estresse com seca e seu cultivo é promissor para a segurança alimentar e nutricional.
Palavras-chave: Índice $\bar{Z}$. Interação genótipo × ambiente. *Phaseolus vulgaris* L. Seleção simultânea.

Introduction

In a scenario of climate change, the expectation is that numerous regions worldwide will experience increased aridity characterized by prolonged droughts, intensified heat, and erratic precipitation patterns (Losa et al., 2022). As a consequence, drought stress has emerged as the primary abiotic factor of concern within breeding programs.

Globally, common bean (*Phaseolus vulgaris* L.) production predominantly takes place in growing environments prone to stress, featuring intermittent or terminal drought conditions (S. E. Beebe et al., 2013). Given that common bean represents the most widely consumed legume globally, particularly serving as an alternative protein source to animal protein, addressing drought stress has become one of the main objectives in contemporary common bean breeding programs.

Under drought conditions, a reduction in grain yield components (Diaz et al., 2022; Gonçalves et al., 2022), plant height, cycle, leaf area, and grain yield (Gonçalves et al., 2022; Smith et al., 2019) has been observed in common bean genotypes. Therefore, in growing conditions that involve prolonged water restrictions, a significant decrease in global common bean production is anticipated. This is particularly pertinent as common bean cultivation is predominantly carried out in family-farming settings, which employ minimal agricultural inputs. In this scenario, drought stress may lead to food insecurity for coming generations.

Similarly, drought stress can affect the commercial grain quality of common bean genotypes. Recent studies have reported a decrease in the mass of 100 grains (Diaz et al., 2022; Smith et al., 2019), an increase in cooking time, and greater darkening of the grains (Gonçalves et al., 2022) when common bean genotypes were cultivated under drought stress conditions. However, mineral concentration in the seeds remains unchanged in these genotypes (Diaz et al., 2022; Smith et al., 2019). As common bean grains are an important source of carbohydrates, proteins, minerals, and other nutrients that provide health-promoting effects (Meenu et al., 2023), drought stress can result in nutritional insecurity.

Substantial research efforts have been made in the breeding programs to improve the resilience of common bean to drought. If there is genetic variability for grain quality and mineral concentration in common bean genotypes grown in drought conditions, greater efficiency in selecting drought-resilient lines is expected.

For the most prevalent Mesoamerican common bean types produced in Brazil, carioca (beige seed coat with brown streaks) and black, no preliminary studies were found that aimed to simultaneously select for commercial grain quality traits and mineral concentration under multiple environments in drought stress conditions. It is hypothesized that cultivation under conditions of prolonged water restriction may alter commercial grain quality and mineral concentration in common bean genotypes. Hence, this study was undertaken to investigate the genetic variability of commercial grain quality traits and mineral concentration in Mesoamerican common bean genotypes cultivated under drought stress conditions, as well as to carry out simultaneous selection for multiple traits.

Material and Methods

Plant material and experimental design

Twelve common bean genotypes from the Mesoamerican gene pool were evaluated in this study. These genotypes encompass six elite lines currently under assessment for registration as new cultivars; two cultivars not yet registered for cultivation in Rio Grande do Sul-RS, Brazil, albeit being observed for potential expansion of cultivation area; and four control cultivars already registered for cultivation in RS (Table 1). These genotypes feature carioca or black grains and represent technological innovations from five public breeding programs that participated in the Southern Brazilian Common Bean Network during the 2020-2021 biennium.

Table 1
Name, grain type, institutional origin (Breeding program), genotype identification (Genotype), and registration status in Rio Grande do Sul, Brazil, of the evaluated common bean genotypes

Name	Grain type[1]	Breeding program[2]	Genotype	Registration status
1. IPR Sabiá	Carioca	IDR	Cultivar	Not registered
2. Pérola	Carioca	EMBRAPA	Cultivar	Registered
3. CHC 04-233-2	Carioca	EPAGRI	Elite line	Not registered
4. LEC 03-16	Carioca	UEM	Elite line	Not registered
5. LP 08-186	Carioca	IDR	Elite line	Not registered
6. BRS Esteio	Black	EMBRAPA	Cultivar	Registered
7. BRS Intrépido	Black	EMBRAPA	Cultivar	Registered
8. Fepagro Triunfo	Black	SAPDR	Cultivar	Registered
9. IPR Urutau	Black	IDR	Cultivar	Not registered
10. CHP 12 355-02	Black	EPAGRI	Elite line	Not registered
11. LEP 01-16	Black	UEM	Elite line	Not registered
12. LP 09-180	Black	IDR	Elite line	Not registered

[1]Grain type - Carioca (beige seed coat with brown streaks); Black (black seed coat).
[2]Breeding program - IDR: Rural Development Institute of Paraná; EMBRAPA: Brazilian Agricultural Research Corporation; EPAGRI: Agricultural Research and Rural Extension of Santa Catarina; UEM: State University of Maringá; SAPDR: Secretariat of Agriculture, Livestock, and Rural Development of the State of Rio Grande do Sul.

A randomized-block experimental design was employed, with three repetitions. Each plot comprised four 4-m rows and an area of 8 m². The seeding density was 15 seeds per linear meter, aiming to obtain 48 plants per row and 192 plants per plot. The spacing between plants in the row was 10 cm, and between rows, 50 cm. The central two rows constituted the usable area of each plot, resulting in an effective plot area of 4 m².

Experimental site, meteorological conditions, and field management

The experiments were conducted in Santa Maria-RS, Brazil, during the following growing seasons: 2020 rainy (starting 10/09/2020), 2021 dry (starting 02/23/2021), and 2021 rainy (starting 10/08/2021). In this location, the Value for Cultivation and Use (VCU) experiments of the Southern Brazilian Common Bean Network are conducted at the field area of the Federal University of Santa Maria, situated at 29°42' S latitude, 53°43' W longitude, and 95 m altitude.

The region is characterized by a humid subtropical climate, with well-distributed rainfall throughout the year (Alvares et al., 2013). The climatological normal from 1991 to 2020 indicates average annual temperatures of 18 °C and average annual precipitation of 1,800 mm (Instituto Nacional de Meteorologia [INMET], 2021). The years 2020 and 2021 were influenced by the La Niña climate phenomenon (Jones, 2022), resulting in precipitation below the annual average in RS, Brazil (Matzenauer et al., 2017). In this scenario, water deficit, increased temperature, and greater solar radiation were recorded during critical phenological stages of common bean development, such as emergence, flowering, and pod filling. Figure 1 illustrates the main differences in precipitation, humidity, maximum and minimum temperatures, and solar radiation observed during the period encompassing the three experiments.

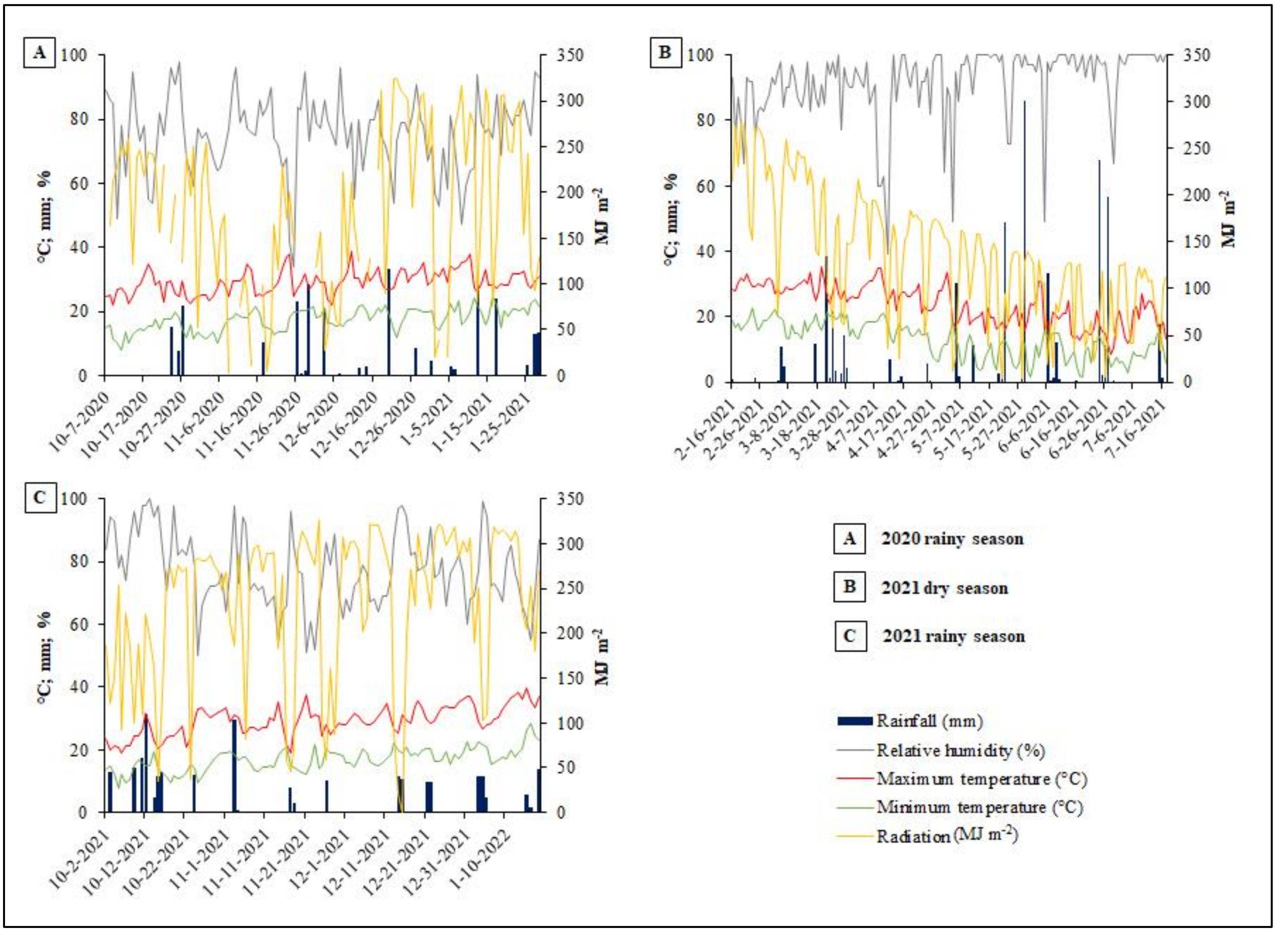

Figure 1. Meteorological data on rainfall (mm), relative humidity (%), maximum and minimum temperature (°C), and radiation (MJ m^{-2}) in the 2020 rainy season (A), 2021 dry season (B), and 2021 rainy season (C) crops, collected in the eighth district at the Santa Maria Meteorology Station, located at the Federal University of Santa Maria (29°42'S, 53°43'W and 95 m of altitude), Rio Grande do Sul, Brazil.

The soil in the experimental area is classified as a typic alitic Argisol, Hapludalf. Prior to initiating the 2020 rainy season experiment, soil samples were collected at a depth of 0 to 20 cm and subjected to physicochemical analysis. The following results were obtained: pH in water = 6.6, organic matter = 0.9%, clay = 26.0%, potassium = 100.0 mg dm^{-3}, phosphorus = 14.4 mg dm^{-3}, calcium = 6.4 cmolc dm^{-3}, magnesium = 3.2 cmolc dm^{-3}, zinc = 0.62 mg dm^{-3}, and copper = 1.42 mg dm^{-3}.

Soil preparation followed conventional methods, using a tractor to perform one plowing followed by two harrowing operations. Fertility adjustments made based on the interpretation of the soil chemical analysis report, according to the recommendations of Comissão de Química e Fertilidade do Solo [CQFS] (2016). Control of invasive plants and pest management were implemented as recommended by Comissão Técnica Sul Brasileira de Feijão [CTSBF] (2012) to ensure optimal crop growth conditions. Irrigation was applied during emergence and flowering to ensure uniform plant stand and improve flower retention, respectively, in the absence of precipitation during these phenological stages.

Harvesting was conducted manually when at least 90% of plants in the usable area exhibited dry pods. Plants harvested from each usable plot were tied together and labeled. These plants remained in a greenhouse until the grains could be manually threshed. The moisture content of all grains was standardized to 13%.

Commercial grain quality

The commercial quality of the grains was evaluated based on 11 traits. Firstly, the mass of 100 grains was determined by weighing 100 randomly sampled grains in three replicates of each repetition. Subsequently, the length (longitudinal distance parallel to the hilum), width (transverse distance perpendicular to the hilum), and thickness (distance between the upper and lower faces of the grain at the hilum center) were measured using a digital caliper, with 10 grains randomly sampled in each repetition. The length/thickness ratio characterized grain shape, while the thickness/width ratio indicated grain flattening (Puerta Romero, 1961).

Grain color was assessed using a random 20-g sample collected from each repetition. This procedure was performed using a portable colorimeter calibrated to the manufacturer's specifications, selecting the color spectrum from the CIE Lab scale. In this scale, L* ranges from 0 (black) to 100 (white), a* from -60 (green) to +60 (red), and b* from -60 (blue) to +60 (yellow). Grains were evenly spread in a petri dish, and the device head was positioned over them. Three readings of L*, a*, and b* were taken from each grain sample in each repetition.

Water absorption and cooking time were ascertained using a random sample of 25 grains per repetition, soaked for 8 h in 50 mL of distilled water at room temperature (20 ± 2 ºC). Water absorption was calculated as the ratio between the initial dry weight of the grains and their final weight after soaking, expressed as a percentage. Cooking time was measured using a 25-plunger Mattson cooker, a device with a base plate containing 25 holes (Proctor & Watts, 1987). Each grain was positioned above a hole and below a plunger, and the cooker was placed inside a pan containing 3 L of boiling distilled water. Individual grains were considered cooked when the plunger dropped and pierced the grain. The average dropping time of the first 13 plungers defined the cooking time for each sample.

Mineral concentration

The concentration of seven minerals was determined: potassium, phosphorus, calcium, magnesium, iron, zinc, and copper. A random sample of 50 g of raw grains from each repetition was ground into fine flour. A 0.5 g sub-sample of this flour underwent acid digestion using a 3:1 mixture of nitric and perchloric acid, respectively, following the methodology described by Miyazawa et al. (2009).

Digestion completion was indicated by each sample displaying approximately 1 mL of translucent liquid. The digestion product was transferred to 50-mL Falcon tubes and completed with distilled water. The following instruments were used to read the mineral concentrations: flame photometer (potassium), optical absorption spectrophotometer (phosphorus), and atomic absorption spectrophotometer (calcium, magnesium, iron, zinc, and copper).

Statistical analyses

Cooking time was recorded in minutes and converted to seconds (s). The normality assumption was not achieved for water absorption (%) data in most evaluated environments, when judged by symmetry, kurtosis, and the Lilliefors test. These data exhibited a Poisson distribution and the following transformation was applied to allow the correct interpretation of the results obtained:

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

in which x is the original value in percentage terms.

Analysis of variance was conducted for all traits assessed across the three growing seasons. For all statistical analyses implemented, a significance level of 0.05 probability was adopted. Residual variances between the three experiments were examined using Hartley's maximum F test. A combined analysis of variance was undertaken for treatments common to all experiments. In this analysis, block and error effects were treated as random, while the effects of genotype, environment, genotype × environment interaction, and mean were considered fixed. In the combined analysis of variance, the phenotypic variation was partitioned into genotype, environment, genotype × environment interaction for all traits evaluated. The Scott-Knott test was applied to categorize common bean genotypes and compare the groups formed for each trait individually.

The $\bar{Z}$ index was estimated with the aim of simultaneously selecting for multiple quantitative traits. Therefore, qualitative traits (shape and degree of flattening of the grains) and those lacking genetic variability (non-significant effect of genotype and/or genotype × environment interaction) were not included in this analysis. Following the exclusion of three traits (shape, degree of grain flattening, and magnesium concentration), the remaining data were standardized per plot, allowing them to be compared directly. The $\bar{Z}$ index was derived according to the formula:

$$Z_{ij} = (Y_{ij} - Y_{.j})/S_j \quad (2)$$

in which

Z_{ij} is the standardized trait value of genotype i (i = 1, 2, ..., 12), in block j (j = 1, 2, 3);

Y_{ij} is the observed value of the trait for genotype i in block j;

$Y_{.j}$ is the overall mean of the 12 genotypes in blocks j; and

S_j is the standard deviation of the trait in block j.

To prevent negative values, a constant equal of three was added to the $\bar{Z}$ index value of each trait, averaged over the three experiments as recommended by Mendes et al. (2009). For each common bean genotype, a plot was generated to illustrate the contribution of each standardized trait to the $\overline{Z}$ index value. $\overline{Z}$ index estimations and figure preparation were conducted using Microsoft® Office Excel; remaining statistical analyses were performed using Genes software (Cruz, 2016).

Results and Discussion

Analysis of variance

Residual variances were heterogeneous across the three growing seasons only for the traits of L*, b*, water absorption, and magnesium concentration. For these four traits, adjustments were made to the degrees of freedom for error and genotype × environment interaction using Genes software (Cruz, 2016). This adjustment resulted in homogeneous residual variances for all 18 evaluated traits, meeting the necessary premise for combined analysis of variance.

A significant genotype effect was observed for all traits except for magnesium concentration (Table 2). For this mineral, the environment was the greatest contributor to the variance (84.88%). Consequently, the magnesium concentration was highly affected under drought stress. A large range of variation has been documented for technological traits (Rana et al., 2015; Rivera et al., 2016; Yeken et al., 2019) and mineral concentration (Delfini et al., 2020, 2021; McClean et al., 2017; Nazir et al., 2022; Yeken et al., 2019) in common bean genotypes. These findings indicate existing genetic variability, enabling the selection of common bean lines with grain commercial quality traits and mineral concentrations that meet current breeding program standards. Additionally, a significant environmental effect was noted for all 18 traits under analysis, consistent with previous reports on technological traits (Delfini et al., 2017; Dias et al., 2021; Ribeiro & Kläsener, 2020) and mineral concentration (Delfini et al., 2021; Dias et al., 2021) in common bean genotypes produced in diverse environments. Significant differences between growing environments indicate that variations between years and seasons, especially those attributed to meteorological conditions (Figure 1), altered the response of common bean genotypes.

A non-significant genotype × environment interaction effect was detected only for thickness, shape, and concentrations of magnesium, iron, zinc, and copper (Table 2). Conversely, for the other analyzed traits, a significant genotype × environment interaction was identified, confirming that common bean genotypes can display variations in many technological and nutritional traits across different environments (Dias et al., 2021; Ribeiro et al., 2023; Ribeiro & Kläsener, 2020). Hence, the efficacy of selecting common bean lines with high commercial grain value and elevated mineral concentration will be more efficient if based on data obtained from multi-environment experiments.

Table 2

Combined analysis of variance containing the degrees of freedom (DF), mean squares (MS), contribution to phenotypic variation (PV, %), mean, coefficient of experimental variation (CEV, %), and selective accuracy (SA) for the following traits: mass of 100 grains (M100G, g), grain length (Length, mm), grain width (Width, mm), grain thickness (Thickness, mm), grain shape (Shape), degree of flatness (Flatness), L* value (L*), a* value (a*), b* value (b*), water absorption (Absorption, %), cooking time (CT, min:s), concentrations of potassium (K, g kg^{-1} of dry matter [DM]), phosphorus (P, g kg^{-1} DM), calcium (Ca, g kg^{-1} DM), magnesium (Mg, g kg^{-1} DM), iron (Fe, mg kg^{-1} DM), zinc (Zn, mg kg^{-1} DM), and copper (Cu, mg kg^{-1} DM) of 11 common bean genotypes evaluated across three experiments carried out 2020 and 2021

	DF	M100G		Length		Width		Thickness		Shape		Flatness	
		MS	PV	MS	PV	MS	PV	MS	PV	MS	PV	MS	PV
B/Env	6	1.38	0.89	0.07	2.20	0.03	1.16	0.03	3.25	0.00	0.12	0.00	0.65
G	10	27.19*	29.33	0.54*	27.40	0.58*	33.51	0.20*	31.07	0.02*	29.85	0.01*	37.22
E	2	181.54*	39.15	3.63*	37.08	4.30*	49.23	0.80*	24.66	0.21*	53.84	0.03*	27.86
G × E	20	8.78*	18.95	0.13*	13.64	0.06*	6.91	0.04^{ns}	12.02	0.00^{ns}	4.31	0.00*	13.89
Error	60	1.80	11.68	0.06*	19.68	0.03	9.19	0.03	28.99	0.00	11.88	0.00	20.38
Mean		23.05		10.26		6.41		4.56		1.61		0.71	
CEV		5.83		2.47		2.55		3.88		2.45		3.61	
SA		0.96		0.94		0.98		0.92		0.97		0.95	

		L*		a*		b*		Absorption		CT		K	
		MS	PV	MS	PV	MS	PV	MS	PV	MS	PV	MS	PV
B/Env	6	1.64	0.04	0.09	0.05	0.16	0.01	0.21	1.74	7392.20	0.93	1.32	5.42
G	10	2749.08*	98.01	90.56*	87.49	756.78*	99.28	1.82*	24.44	188389.72*	39.71	1.70*	11.61
E	2	26.97*	0.19	9.26*	1.79	4.57*	0.12	16.30*	43.72	216613.12*	9.13	21.59*	29.44
G × E	20	29.22*	1.56	5.05*	9.76	1.89*	0.32	1.20*	19.39	68001.59*	28.67	1.53*	20.85
Error	60	1.55	0.20	0.16	0.91	0.72	0.26	0.31	10.71	17048.37	21.56	0.80	32.68
Mean		34.59		3.77		4.95		9.44		1019.79		12.22	
CEV		3.60		10.50		17.15		5.87		12.80		7.31	
SA		1.00		1.00		1.00		0.91		0.95		0.73	

		P		Ca		Mg		Fe		Zn		Cu	
		MS	PV	MS	PV	MS	PV	MS	PV	MS	PV	MS	PV
B/Env	6	0.35	5.96	0.02	2.24	0.00	0.15	23.10	3.38	10.23	5.65	1.34	3.33
G	10	0.89*	25.46	0.24*	39.59	0.02^{ns}	2.98	85.43*	20.86	29.01*	26.71	1.70*	7.07
E	2	6.45*	36.92	0.94*	30.69	2.81*	84.88	234.90*	11.47	148.27*	27.30	87.11*	72.28
G × E	20	0.21*	11.96	0.04*	12.28	0.01^{ns}	1.61	33.30^{ns}	16.26	7.81^{ns}	14.38	0.60^{ns}	5.03
Error	60	0.11	19.69	0.01	15.20	0.03	10.39	32.78	48.03	4.70	25.95	0.49	12.29
Mean		4.53		1.00		1.18		53.67		24.96		7.52	
CEV		7.46		12.48		15.02		10.67		8.68		9.34	
SA		0.93		0.97		0.00		0.79		0.92		0.84	

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

The observed coefficient of experimental variation ranged from 2.45% (shape) to 17.15% (b*), indicating high to moderate experimental precision as per the classifications proposed by Pimentel-Gomes (1990). Selective accuracy, on the other hand, ranged from 0 (magnesium concentration) to 1 (L*, a*, and b*), with values closer to 1 associated with greater experimental precision. Low experimental precision was solely noted for magnesium concentration, based on the selective accuracy classes described by Resende and Duarte (2007). For the remaining traits, selective accuracy values of ≥ 0.73 were obtained, characterizing high or very high experimental precision. Thus, the majority of the investigated traits showed high experimental precision when considering both the coefficient of experimental variation and selective accuracy statistics. This low experimental error in determining commercial grain quality traits and mineral concentration allows for greater accuracy in the selection of superior common bean lines for breeding purposes.

Genetic variability for commercial grain quality traits

When the genotype × environment interaction was significant, it was evident that the common bean genotypes did not consistently maintain commercial grain quality traits across different growing seasons (Tables 3 and 4). Despite this, carioca grain cultivars IPR Sabiá and Pérola and black grain cultivars BRS Esteio and IPR Urutau were classified in the group of genotypes with the highest values for mass of 100 grains across the three growing seasons (Table 3). Nevertheless, none of the evaluated common bean genotypes exhibited a mass of 100 grains ≥ 25 g in all three growing seasons, which aligns with the selection standards used in breeding programs for carioca and black grain cultivars (Carbonell et al., 2010; Pereira et al., 2021; Ribeiro & Kläsener, 2020). Mass of 100 grains varied when common bean genotypes were cultivated in multi-environment experiments (Dias et al., 2021; F. D. C. Silva et al., 2023), indicating that this is a quantitative trait greatly influenced by the growing environment.

Table 3
Mean values obtained for mass of 100 grains (M100G), grain length (Length), grain width (Width), grain thickness (Thickness), grain shape (Shape), degree of flatness (Flatness), L* value (L*), and a* value (a*) in 12 common bean genotypes evaluated across three growing seasons (2020 rainy season [20RS], 2021 dry season [21DS], and 2021 rainy season [21RS])

Genotype	M100G (g)			Length (mm)			Width (mm)		
	20RS	21DS	21RS	20RS	21DS	21RS	20RS	21DS	21RS
Carioca bean genotypes									
IPR Sabiá	24.51a	25.16a	20.07a	10.64a	10.51a	9.89b	6.41a	6.81a	5.97b
Pérola	25.53a	26.13a	20.58a	10.63a	10.60a	10.50a	6.29a	6.90a	6.21a
CHC 04-233-2	19.04b	25.84a	21.35a	10.52a	10.02b	10.30a	6.20a	6.73a	6.31a
LEC 03-16	19.40b	22.46c	14.68b	10.03b	9.87b	9.39b	5.60b	6.20b	5.38c
LP 08-186	23.77a	-	19.64a	10.05b	-	9.46b	6.63a	-	6.36a
Black bean genotypes									
BRS Esteio	26.19a	24.96a	20.44a	10.74a	10.03b	9.73b	6.80a	7.00a	6.48a
BRS Intrépido	26.06a	24.13b	21.51a	10.63a	10.33a	10.29a	6.44a	6.84a	6.24a
Fepagro Triunfo	27.08a	24.17b	22.83a	10.80a	10.50a	9.94b	6.57a	6.88a	6.07a
IPR Urutau	27.12a	25.80a	22.93a	11.04a	10.65a	10.11a	6.57a	6.76a	6.24a
CHP 12 355-02	24.91a	22.84c	20.71a	10.46a	10.02b	9.72b	6.53a	6.90a	6.17a
LEP 01-16	25.80a	22.27c	20.29a	10.60a	10.07b	9.63b	6.40a	6.64a	5.90b
LP 09-180	24.14a	23.25c	18.38a	10.35b	10.58a	9.65b	6.16a	7.05a	5.88b
	Thickness	Shape	Flatness	L*			a*		
	Mean (mm)	Mean	Mean	20RS	21DS	21RS	20RS	21DS	21RS
Carioca bean genotypes									
IPR Sabiá	4.51b	Elliptical	Semi-full	53.99b	61.56a	55.47b	10.21a	5.57a	8.84b
Pérola	4.58b	Elliptical	Semi-full	52.21b	62.30a	53.89c	10.25a	5.62a	9.34b
CHC 04-233-2	4.63b	Elliptical	Semi-full	49.70c	60.30b	52.02d	10.07a	5.43a	9.98a
LEC 03-16	4.37c	Elliptical	Semi-full	60.60a	58.51c	58.44a	5.89b	4.78b	5.27c
LP 08-186	-	Elliptical	Flattened	52.11b	-	53.49c	11.03a	-	9.05b
Black bean genotypes									
BRS Esteio	4.62b	Elliptical	Flattened	22.80d	20.75e	22.25e	1.06d	1.68d	1.11e
BRS Intrépido	4.63b	Elliptical	Semi-full	22.85d	20.92e	22.13e	1.42d	1.77d	1.40e
Fepagro Triunfo	4.57b	Elliptical	Semi-full	23.38d	22.32d	22.17e	2.77c	2.74c	2.24d
IPR Urutau	4.83a	Elliptical	Semi-full	22.18d	20.80e	21.97e	1.11d	1.74d	1.11e
CHP 12 355-02	4.36c	Elliptical	Flattened	22.78d	20.87e	22.10e	1.20d	2.11d	1.36e
LEP 01-16	4.67b	Elliptical	Semi-full	21.75d	21.97d	22.15e	1.23d	1.58d	1.10e
LP 09-180	4.35c	Elliptical	Flattened	22.22d	21.67d	22.43e	1.20d	2.02d	1.24e

* Means followed by the same letter in each column do not differ significantly from each other by the Scott-Knott's test, at 5% probability.

Table 4

Mean values obtained for b* value (b*), water absorption (Absorption), cooking time (CT), and concentrations of potassium (K), phosphorus (P), and calcium (Ca) in 12 common bean genotypes evaluated across three growing seasons (2020 rainy season [20RS], 2021 dry season [21DS], and 2021 rainy season [21RS])

Genotype	b*			Absorption (%)			CT (min:s)		
	20RS	21DS	21RS	20RS	21DS	21RS	20RS	21DS	21RS
Carioca bean genotypes									
IPR Sabiá	17.24a	17.43b	16.39a	101.15a	78.17a	99.97a	17:23c	13:46c	17:29a
Pérola	17.63a	18.44a	16.72a	102.13a	86.86a	102.66a	17:16c	11:53c	17:25a
CHC 04-233-2	14.76b	17.16b	16.41a	99.14a	83.69a	92.11b	18:38c	12:14c	15:03b
LEC 03-16	15.16b	17.02b	13.58b	112.24a	94.46a	98.93a	12:43d	09:36c	13:28b
LP 08-186	17.91a	-	16.64a	102.08a	-	93.19b	16:40c	-	15:51b
Black bean genotypes									
BRS Esteio	-1.69c	-1.70c	-1.85c	95.92a	45.24b	93.12b	20:45b	25:10a	18:41a
BRS Intrépido	-1.67c	-1.62c	-1.76c	98.04a	82.45a	92.64b	17:22c	16:43b	17:53a
Fepagro Triunfo	-1.89c	-1.56c	-1.89c	90.32a	54.64b	89.93b	17:33c	18:19b	17:32a
IPR Urutau	-1.63c	-1.60c	-1.62c	96.01a	81.52a	94.96b	18:46c	15:54b	15:22b
CHP 12 355-02	-1.50c	-1.77c	-1.70c	99.48a	91.34a	95.05b	23:10a	11:52c	20:49a
LEP 01-16	-1.49c	-1.43c	-1.55c	96.59a	58.08b	86.05b	20:01b	18:38b	16:49a
LP 09-180	-1.72c	-1.35c	-1.58c	93.88a	71.34a	92.91b	18:24c	18:11b	16:23b
	K (g kg^{-1} of dry matter)			P (g kg^{-1} of dry matter)			Ca (g kg^{-1} of dry matter)		
	20RS	21DS	21RS	20RS	21DS	21RS	20RS	21DS	21RS
Carioca bean genotypes									
IPR Sabiá	11.07a	10.56b	12.98a	3.48b	4.75b	4.38a	0.85b	0.88a	1.24b
Pérola	10.93a	12.76a	12.91a	4.38b	5.09b	4.61a	0.93a	0.99a	1.12c
CHC 04-233-2	11.92a	12.25a	12.83a	4.58b	4.84b	4.45a	0.93a	0.84a	0.96d
LEC 03-16	11.95a	13.57a	13.13a	5.36a	6.01a	4.71a	0.43c	0.69a	0.83d
LP 08-186	10.05a	-	12.25b	4.14b	-	4.36a	0.76b	-	1.14c
Black bean genotypes									
BRS Esteio	11.66a	13.86a	12.54a	3.88b	5.22b	4.58a	1.10a	0.86a	1.55a
BRS Intrépido	11.70a	13.13a	12.47a	4.17b	4.88b	4.33a	0.98a	1.02a	1.34b
Fepagro Triunfo	10.38a	13.64a	11.37b	3.69b	4.92b	4.24a	1.06a	0.94a	1.50a
IPR Urutau	11.26a	11.33b	12.47a	4.32b	4.56b	4.37a	1.02a	1.01a	1.29b
CHP 12 355-02	10.74a	13.13a	11.95b	3.92b	4.78b	4.15a	1.18a	0.96a	1.27b
LEP 01-16	11.07a	12.91a	13.13a	3.99b	5.28b	4.47a	0.70b	0.85a	0.99d
LP 09-180	11.55a	13.27a	12.98a	3.98b	4.91b	4.37a	0.82b	0.77a	1.04c

* Means followed by the same letter in each column do not differ significantly from each other by the Scott-Knott's test, at 5% probability.

In the 2021 rainy season, a period marked by the lowest precipitation levels recorded during crop development (Figure 1), a mass of 100 grains ≤ 22.93 g was observed for all common bean genotypes (Table 3). Therefore, under conditions of prolonged water restriction (2021 rainy season), there was a decrease in mass of 100 grains for all common bean genotypes. Previous studies have also reported that drought stress reduces mass of 100 grains in common bean genotypes (Diaz et al., 2022; Smith et al., 2019). This is explained by physiological limitations that occur during the grain-filling stage under drought conditions. Water deficit induces stomatal closure, decreasing CO_2 assimilation and limiting the production and translocation of photoassimilates to developing seeds, which directly reduces grain yield and grain weight in common bean genotypes (Rosales et al., 2012). These findings highlight the challenges expected in selecting new common bean cultivars with increased mass of 100 grains in a climate change scenario characterized by longer drought periods, more intense heat, and irregular precipitation (Losa et al., 2022).

One carioca grain cultivar (Pérola) and two black grain cultivars (BRS Intrépido and IPR Urutau) formed a group characterized by grains with greater length and width across three growing seasons (Table 3). However, only cultivar Urutau stood out for its grain thickness over the average of the three seasons. The ratios of these grain dimensions, which define their shape and degree of flattening, are qualitative traits highly appreciated by consumers of common bean. All genotypes exhibited an elliptical shape, with the majority showing a semi-full profile, aligning with the grain standards prioritized in breeding programs for carioca and black grains (Carbonell et al., 2010). However, lines LP 08-186, CHP 12 355-02, LP 09-180, and cultivar BRS Esteio displayed flattened grains, a trait that reduces market acceptance. In common bean, the standards for different commercial grain classes have been established by breeding programs to fulfill consumer preferences. A survey among carioca grain consumers indicated a preference for medium-sized grains (25 to 30 g), elliptical shape, and a semi-full profile (Ribeiro et al., 2019). Grain traits desired by consumers are essential for a new common bean cultivar to be registered for cultivation.

Another visual trait of great importance to common bean consumers is the color of the grains. For carioca grains, L* values varied from 49.70 (CHC 04-233-2; 2020 rainy season) to 62.30 (Pérola; 2021 dry season) (Table 3). Higher L* values represent greater lightness, i.e., lighter grains, a trait highly valued in carioca grains. Among the carioca common bean genotypes, only line LEC 03-16 consistently achieved L* ≥ 55.00 across all three growing seasons, conforming to the lightness standard recommended by Arns et al. (2018) for this grain type. These authors also proposed that carioca grains should be slightly red (a* ≤ 7.00) and slightly yellow (b* ≤ 16.00). Only line LEC 03-16 adequately met the criteria for a* across all three growing seasons (Table 3) and for b* in the two rainy season crops (Table 4). The genotype accounted for the largest contribution to phenotypic variance in the values of L* (98.01%), a* (87.49%), and b* (99.28%) (Table 2), highlighting that the color of common bean grains is minimally affected under drought conditions. Line LEC 03-16 distinguished itself by having grain color values (L*, a*, and b*) that meet the objectives of breeding programs for carioca grains, and due to the increased lightness of its grains, it is likely to be more acceptable to consumers.

In this study, it was observed that carioca common bean genotypes displayed notably light grains (L* ≥ 58.51) when grown during the 2021 dry season (Table 3). This is likely attributable to the reduced solar radiation intensity during the period preceding the harvest (Figure 1). Similarly, carioca common bean lines cultivated in the dry season exhibited lighter grains compared to those from the rainy season in RS, Brazil (Ribeiro et al., 2023), confirming that environmental variables prevailing during cultivation influence grain color. These results suggest the feasibility of producing lighter carioca grains in the dry conditions of southern Brazil, adding value to the marketed grains.

For black grains, a narrower range of variation in L* values was recorded, ranging from 20.75 (BRS Esteio; 2021 dry season) to 23.38 (Fepagro Triunfo; 2020 rainy season) (Table 3). No black common bean genotype reached an L* value ≤ 22.00 across three growing seasons, failing to meet the lightness standards required for this grain type (Ribeiro et al., 2003). This limitation can be attributed to the low genetic variability for stable black coloration among the common bean genotypes evaluated under drought stress. Furthermore, these genotypes displayed positive a* values (1.06 to 2.77), that is, slightly reddish, and negative b* values (-1.89 to -1.35), i.e., slightly blue (Table 4), resulting in a purplish color. Ideally, black grains should display low lightness (L* ≤ 22.00) and no secondary coloration (a* and b* values near zero) to maintain a uniform black appearance. The occurrence of purplish grains, often associated with long storage and slow cooking of black grains, leads to their rejection. None of the black common bean genotypes demonstrated a grain color (L*, a*, and b*) that met the selection criteria adopted by breeding programs over the three growing seasons.

The evaluated common bean genotypes showed considerable genetic variability in water absorption, ranging from 45.24% (BRS Esteio; 2021 dry season) to 112.24% (LEC 03-16; 2020 rainy season) (Table 4). Comparable water absorption rates were reported for various carioca and black common bean genotypes grown in different environments (Ribeiro et al., 2023; Santos et al., 2016). The mean clustering test was unable to distinguish between genotypes based on water absorption at the same significance level in the 2020 rainy season. During this season, all common bean genotypes showed high water absorption rates (≥ 90.32%), resulting in the formation of a single group. Advanced drought-tolerant common bean lines exhibited high water absorption after the grains were soaked in water (Gathu et al., 2012). The speed of water absorption is important in the canning industry, as it enables rapid and uniform grain expansion during soaking.

Line LEC 03-16 and cultivar IPR Sabiá exhibited water absorption rates similar to those of cultivar Pérola (carioca grain control), and were categorized in the group of fast water absorption across all three growing seasons. Typically, genotypes that absorb more water have a shorter cooking time, as water absorption is inversely correlated with cooking time in common bean (Kläsener et al., 2022; Ribeiro & Kläsener, 2020). Additionally, significant genotype × environment interactions for water absorption have been documented in common bean (Kläsener et al., 2022; Ribeiro et al., 2023; Ribeiro & Kläsener, 2020). Therefore, identifying common bean lines with consistently high water absorption, irrespective of the growing environment, remains a major challenge for breeding programs.

Cooking time varied among carioca and black common bean genotypes, ranging from 09 min and 36 s to 23 min and 10 s (Table 4). A broader variation in cooking time has been noted in the literature for Andean common bean genotypes, with some requiring over 60 min for cooking (Berry et al., 2020; Cichy et al., 2019). In contrast, for Mesoamerican common bean genotypes, including carioca and black grains, a cooking time of less than 36 min has been reported (Santos et al., 2016; M. B. O. Silva et al., 2016; Ribeiro et al., 2023). The existence of genetic variability allows for the development of common bean lines with shorter cooking times, catering to different commercial grain classes.

For both carioca and black grains, the selection criteria proposed by Santos et al. (2016) to characterize fast cooking is 25 min. The present study demonstrates that all evaluated common bean genotypes qualify as fast-cooking, thus meeting the demands of the consumer market and the industry. This result highlights the success of breeding programs in reducing cooking time. Developing new fast-cooking cultivars contributes to sustainability by lowering the consumption of firewood, gas, or electricity required for preparing a meal.

Genetic variability for mineral concentration

The common bean genotypes varied in potassium concentration (10.05 to 13.86 g kg^{-1} of dry matter – DM) across the growing seasons (Table 4). This variation range is similar to that found in commercial common bean cultivars (Ribeiro et al., 2022a, 2023) but lower than values reported in common bean landraces (Zilio et al., 2017) grown in Brazil, suggesting potential genetic erosion in potassium concentration. This is justified by the fact that the main focus of common bean breeding programs remains on increasing grain yield, with limited investment in genetic biofortification.

However, lines CHC 04-233-2, LEC 03-16, LEP 01-16, and LP 09-180, along with cultivars Pérola, BRS Esteio, and BRS Intrépido, exhibited potassium concentrations ≥ 12 g kg^{-1} DM in both the 2021 dry and rainy season crops, a benchmark often used to indicate high concentration of this mineral in the grains (Steckling et al., 2017). In the current study, there was no significant variation in potassium concentrations among the common bean genotypes grown during the 2021 rainy season, during which extended periods of water restriction were recorded (Figure 1). Recent research confirms that dry cultivation conditions do not significantly affect the concentration of various minerals in common bean (Diaz et al., 2022; Smith et al., 2019). Hence, it is possible to select common bean lines with enhanced mineral concentration, irrespective of the prevailing water regime. As potassium plays a critical role in managing hypertension (McDonough & Fenton, 2022), developing common bean lines with a higher concentration of this mineral could offer health benefits.

The lowest phosphorus concentration was noted in cultivar IPR Sabiá in the 2020 rainy season (3.48 g kg^{-1} DM), while the highest was observed in line LEC 03-16 in the 2021 dry season (6.01 g kg^{-1} DM) (Table 4). These values are similar to phosphorus concentrations found in common bean genotypes produced in different environments (Delfini et al., 2021; Ribeiro et al., 2022a, 2023; Zilio et al., 2017). These findings suggest less genetic variability for phosphorus concentration in common bean, posing challenges for biofortification with this mineral.

Four common bean genotypes were highlighted for their phosphorus concentration (≥ 5.0 g kg^{-1} DM) in the 2021 dry season: Pérola, LEC 03-16, BRS Esteio, and LEP 01-16, meeting the standard selection criterion for high phosphorus concentration in the grains (Steckling et al., 2017). Only line LEC 03-16 also demonstrated high phosphorus concentration in the 2020 rainy season, making it the most promising line for genetic biofortification programs. Phosphorus is important for the health of bones, teeth, and cardiac and skeletal muscles (Serna & Bergwitz, 2020), which is why increasing the concentration of this mineral has been incorporated as a goal in common bean breeding programs.

Calcium was the element whose concentration varied the least among the macrominerals evaluated, ranging from 0.43 g kg^{-1} DM (LEC 03-16; 2020 rainy season) to 1.55 g kg^{-1} DM (BRS Esteio; 2021 rainy season) (Table 4). Similarly, lower genetic variability for calcium concentration was noted in common bean genotypes (Delfini et al., 2021; Ribeiro et al., 2023; Ribeiro & Kläsener, 2020). In the current study, it was not possible to select any common bean genotype with a high calcium concentration (≥ 1.4 g kg^{-1} DM), based on the standard proposed by Ribeiro et al. (2013), across the three growing seasons. This suggests that the predominantly cultivated grain types in Brazil, carioca and black, have a narrow genetic base for calcium concentration in the grains, potentially hindering the selection of calcium-biofortified lines.

Two carioca common bean genotypes, cultivar Pérola and line LEC 03-16, were placed in the group with the highest iron and copper concentration values, with only line LEC 03-16 also being notable for its zinc concentration (Table 5). The following black common bean genotypes were simultaneously allocated to the groups with the highest iron and copper concentrations: BRS Esteio, BRS Intrépido, and LEP 01-16. None of the common bean genotypes evaluated exhibited iron concentrations ≥ 90 mg kg^{-1} DM (Amongi et al., 2023) or zinc concentrations ≥ 32 mg kg^{-1} DM (S. Beebe, 2020), which align with the latest standards for iron and zinc biofortification programs for common bean. For copper concentration, the reference value used in the biofortification of this mineral was not located in the literature. These results indicate that biofortification for microminerals was not considered in the development of the common bean genotypes analyzed in the current study.

Table 5
Mean values obtained for the concentrations of magnesium (Mg), iron (Fe), zinc (Zn), and copper (Cu) in 12 common bean genotypes assessed in the mean of three experiments carried out from 2020 to 2021

Genotype	Mg	Fe	Zn	Cu
	g kg^{-1} of dry matter	... mg kg^{-1} of dry matter...		
		Carioca bean genotypes		
IPR Sabiá	1.20^{ns}	53.48b	24.70b	7.02b
Pérola	1.21	56.72a	24.96b	7.70a
CHC 04-233-2	1.20	52.31b	25.36b	7.24b
LEC 03-16	1.08	54.84a	29.71a	8.38a
LP 08-186	-	-	-	-
		Black bean genotypes		
BRS Esteio	1.13	59.62a	25.17b	7.72a
BRS Intrépido	1.16	55.48a	25.10b	7.55a
Fepagro Triunfo	1.15	50.90b	23.82b	7.11b
IPR Urutau	1.24	50.31b	24.05b	6.99b
CHP 12 355-02	1.17	50.31b	23.83b	7.36b
LEP 01-16	1.16	55.76a	25.33b	8.04a
LP 09-180	1.24	50.67b	22.55b	7.65a

* Means followed by the same letter in each column do not differ significantly from each other by the Scott-Knott's test, at 5% probability.

The average iron, zinc, and copper concentrations found in the common bean genotypes were lower than those previously reported for common bean genotypes of different grain types (Delfini et al., 2021; McClean et al., 2017). These results suggest that micromineral biofortification was not an objective of the breeding programs that developed the genotypes evaluated in the Southern Brazilian Network VCU experiment in the 2020-2021 biennium.

Simultaneous selection for multiple traits

Simultaneous selection for commercial grain quality traits and mineral concentration is a recent focus in common bean breeding programs. To achieve this goal, different selection indices have been utilized to identify standout common bean lines regarding various traits (Dias et al., 2021; Ribeiro et al., 2022b, 2023; Ribeiro & Kläsener, 2020). The $\bar{Z}$ index methodology allows for the selection of lines with multiple favorable traits by providing a visual assessment of easy-to-interpret figures.

Line LEC 03-16 displayed the largest number of traits with $\bar{Z}$ indices favorable for selection aimed at high commercial grain quality and higher mineral concentrations in carioca grains (Figure 2). This line is characterized by very light (> L*), slightly red (< a*), and yellow (b*) grains, which also showed greater water absorption and a shorter cooking time. It further distinguished itself with the highest concentrations of potassium, phosphorus, zinc, and copper. However, this line had the lowest $\bar{Z}$ index for mass of 100 grains as well as grain length, width, and thickness, which is unfavorable for selection. Line LEC 03-16 has small grains, which limits its direct commercial acceptance and restricts its release as a new cultivar. As a consequence, to develop new carioca common bean lines with high commercial grain quality and greater mineral concentrations, it is advisable to use line LEC 03-16 in controlled crosses with common bean genotypes that have medium-sized grains (mass of 100 grains > 25 g).

The black common bean cultivars IPR Urutau and BRS Esteio were highlighted for their commercial grain quality and mineral concentration, respectively (Figure 2). Cultivar IPR Urutau exhibited higher $\bar{Z}$ indices for mass of 100 grains, length, thickness, and water absorption, and lower $\bar{Z}$ indices for L*, a*, and cooking time. This cultivar possesses desirable traits for black grains, namely, greater mass of 100 grains and water absorption, very dark grains, and reduced cooking time. Conversely, cultivar BRS Esteio was prominent for having the highest $\bar{Z}$ indices for the seven minerals evaluated. Crossing these cultivars, IPR Urutau and BRS Esteio, is advantageous for producing recombinants that combine high commercial grain quality with increased mineral concentration.

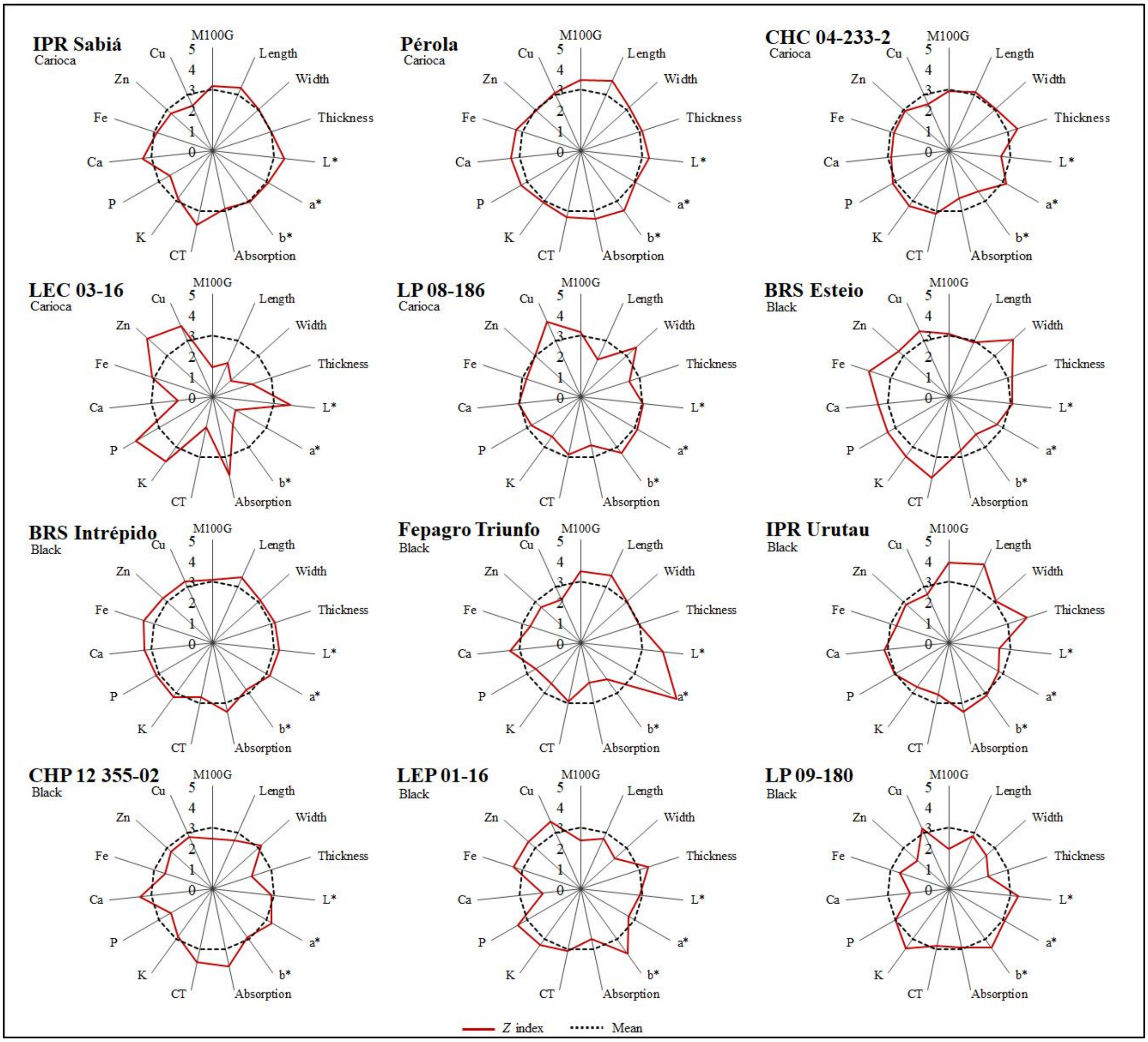

Figure 2. Representation of the Z index for mass of 100 grains (M100G, g), grain length (Length, mm), grain width (Width, mm), grain thickness (Thickness, mm), L* value (L*), a* value (a*), b* value (b*), water absorption (Absorption, %), cooking time (CT, min:s), concentrations of potassium (K, g kg^{-1} of dry matter [DM]), phosphorus (P, g kg^{-1} DM), calcium (Ca, g kg^{-1} DM), iron (Fe, mg kg^{-1} DM), zinc (Zn, mg kg^{-1} DM), and copper (Cu, mg kg^{-1} DM) of five carioca and seven black common bean genotypes assessed in the mean of three experiments carried out from 2020 to 2021.

Conclusions

Carioca and black common bean genotypes demonstrate genetic variability for all commercial grain quality traits and mineral concentrations, except for magnesium. Under cultivation conditions with prolonged water restriction, a reduction in mass of 100 grains is observed, although mineral concentrations in the genotypes remain unchanged.

Line LEC 03-16 possesses the largest number of traits that confer high commercial quality to carioca grains and has the highest concentrations of potassium, phosphorus, zinc, and copper. Cultivar IPR Urutau leads in the commercial quality of black grains, while cultivar BRS Esteio stands out for the highest concentrations of potassium, phosphorus, calcium, iron, zinc, and copper.

Line LEC 03-16 and cultivars IPR Urutau and BRS Esteio are indicated for use in targeted crosses to generate recombinants with high genetic variability for drought resilience. LEC 03-16 and BRS Esteio exhibit higher mineral concentrations under drought stress, and their cultivation is promising for food and nutritional security.

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