Ciências Agrárias
SEMINA

DOI: 10.5433/1679-0359.2025v46n4p1167

# Genetic diversity for commercial grain quality and minerals in common bean cultivars released in Brazil in the last 40 years and selection of superior parents

# Diversidade genética para qualidade comercial de grãos e minerais de cultivares de feijão lançadas no Brasil nos últimos 40 anos e a seleção de parentais superiores

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## Highlights

Mass of 100 grains and iron concentration are efficient descriptors for common bean.
There is genetic diversity among cultivars for commercial grain quality and minerals.
Principal component analysis identifies five groups of common bean cultivars.
Cultivars IPR Juriti, BRS Expedito, BRS Valente, and IPR Tuiuiú are superior parents.

## Abstract

Expanding the knowledge of the genetic diversity of common bean cultivars released as a result of research into commercial grain quality traits and mineral concentration is important for food and nutritional security for future generations. The objectives of this study were to examine the genetic diversity of common bean cultivars in relation to commercial grain quality traits and mineral concentration and to select superior parents. A total of 17 traits (commercial grain quality and minerals) were determined in the 25 common bean cultivars released for cultivation in Brazil over the last 40 years. The cultivars showed genetic variability for all traits, except for normal grains. Mass of 100 grains and iron concentration were the most efficient descriptors for differentiating the cultivars. Principal component analysis identified five groups of common bean cultivars with significant differences in commercial grain quality and mineral concentration. There is genetic diversity among common bean cultivars released in Brazil in the last 40 years for commercial grain quality traits and mineral concentration. The cultivars IPR Juriti, BRS Expedito, BRS Valente, and IPR Tuiuiú stand out for their superior commercial grain quality and also exhibit high potassium concentration (≥ 12.00 g $kg^{-1}$ of dry matter) and will be selected as parents for use in crossing blocks.

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Received: Dec. 06, 2024 Approved: Aug. 08, 2025

**Key words:** Genetic variability. Genotype × environment interaction. *Phaseolus vulgaris.* Principal components. Selection index.

## Resumo

O maior conhecimento da diversidade genética de cultivares de feijão lançadas pela pesquisa para caracteres de qualidade comercial de grãos e concentração de minerais é importante visando a segurança alimentar e nutricional das próximas gerações. Os objetivos deste trabalho foram avaliar a diversidade genética de cultivares de feijão em relação a caracteres de qualidade comercial de grãos e concentração de minerais e selecionar parentais superiores. Um total de 17 caracteres (qualidade comercial de grãos e minerais) foram determinados em 25 cultivares de feijão lançadas para o cultivo no Brasil nos últimos 40 anos. As cultivares apresentaram variabilidade genética para todos os caracteres, exceto para grãos normais. A massa de 100 grãos e a concentração de ferro foram os descritores mais eficientes para diferenciar as cultivares de feijão. A análise de componentes principais identificou cinco grupos de cultivares de feijão com diferenças significativas em qualidade comercial de grãos e concentração de minerais. Existe diversidade genética entre as cultivares de feijão lançadas no Brasil nos últimos 40 anos para qualidade comercial de grãos e concentração de minerais. As cultivares IPR Juriti, BRS Expedito, BRS Valente e IPR Tuiuiú se destacam pela sua superior qualidade comercial de grãos e também exibem alta concentração de potássio (≥ 12,00 g $kg^{-1}$ de matéria seca) e serão selecionadas como parentais para uso em blocos de cruzamento.
**Palavras-chave:** Componentes principais. Índice de seleção. Interação genótipo × ambiente. *Phaseolus vulgaris.* Variabilidade genética.

## Introduction

Common bean (*Phaseolus vulgaris* L.) is the most produced and consumed legume in the world (Losa et al., 2022). Common bean grains are widely used in the human diet as a protein source alternative to animal-derived protein. Besides protein, the grains contain carbohydrates, minerals, vitamins, dietary fiber, and other important nutrients that provide health-promoting effects (Meenu et al., 2023).

Due to its high nutritional value, common bean was included in the group of priority species for biofortification by the HarvestPlus Program of the Consultative Group on International Agricultural Research (CGIAR). Increasing the iron and zinc concentrations in common bean has been a key objective to mitigate deficiencies of these microminerals, which particularly affect people in Latin America and Africa (Beebe, 2020).

However, when a common bean cultivar is released for cultivation in Brazil, the Ministry of Agriculture and Livestock does not mandate the disclosure of its mineral composition during the registration process (Ministério da Agricultura e Pecuária [MAPA], 2006). As a result, the nutritional value of common bean cultivars has been exclusively evaluated in terms of protein content. This has led to a gap in knowledge regarding the mineral concentration of common bean cultivars currently included in the Brazilian diet.

While Brazil boasts a great diversity of *P. vulgaris* L. grain types under cultivation, two grain types carioca (beige seed coat with brown streaks) and black, together account for 85% of the total cultivated common bean area (Pereira et al., 2021). As a consequence, these two primary grain types are also the most consumed in the country. In view of this, breeding programs have channeled greater efforts into the development of carioca and black beans featuring high commercial grain quality traits. This is because the color, size and shape of the grains, in addition to the cooking time, are determining factors that define the purchase of consumers (Kläsener et al., 2020).

Furthermore, the characterization of genetic diversity for commercial grain quality and mineral concentration has been restricted to lines (Ribeiro & Maziero, 2023a) and landraces (Ribeiro et al., 2021) of common bean. No previous studies have analyzed the genetic diversity of these traits in common bean cultivars released by research in Brazil. Detailed characterization of commercial grain quality traits and mineral concentration in common bean cultivars cultivated in Brazil over the last 40 years is warranted to ensure food and nutritional security for future generations. The objectives of this study were to investigate the genetic diversity of common bean cultivars in relation to commercial grain quality traits and mineral concentration as well as to select superior parents.

## Materials and Methods

### *Plant material and experimental design*

Twenty-five common bean cultivars released for cultivation in Brazil over the past 40 years were evaluated in this study (Table 1). These cultivars, developed by five public breeding programs, represent the grain types most produced in Brazil: carioca, black, and cranberry (cream seed coat with red streaks).

**Table 1**
**Common bean cultivars evaluated, genealogy, breeding program (Program), gene pool, grain type, and year of release for cultivation in Brazil (Year)**

| Cultivar | Genealogy | Program[1] | Gene pool | Grain type | Year |
|---|---|---|---|---|---|
| BRSMG Realce | PR 95105259/PR 93201472 | EMBRAPA | Andean | Cranberry | 2011 |
| Iraí | Selection in producer´s crops (Rio Grande do Sul) | DDPA | Andean | Cranberry | 1981 |
| BRSMG Pioneiro | Backcrossing Rudá (recurrent)/ Ouro Negro | EMBRAPA | Mesoamerican | Carioca | 2005 |
| IPR Siriri | IAPAR 31/IAC Akitã | IDR | Mesoamerican | Carioca | 2007 |
| SCS 205 Riqueza | BRS Campeiro/IAC Tybatã | EPAGRI | Mesoamerican | Carioca | 2015 |
| IAC Imperador | [(IAC Carioca Eté/Carioca Precoce)/IAC Carioca Eté]/60 Dias | IAC | Mesoamerican | Carioca | 2012 |

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|---|---|---|---|---|---|
| IPR Juriti | BAT93/2/Carioca Sel.99/Great Northen Nebraska 1 sel#27/3/ sel. Aroana/4/A176/A259/5/ II133/XAN87 | IDR | Mesoamerican | Carioca | 2002 |
| Pérola | Selection in the cultivar Aporé | EMBRAPA | Mesoamerican | Carioca | 1996 |
| BRS Estilo | EMP 250/4/A 769///A 429/XAN S52//V 8025/PINTO VI 114 | EMBRAPA | Mesoamerican | Carioca | 2006 |
| IAC Milênio | BRSMG Majestoso/Gen 96A98-15-3-52-1 | IAC | Mesoamerican | Carioca | 2013 |
| IPR Tangará | LP 95-92/Pérola | IDR | Mesoamerican | Carioca | 2008 |
| Fepagro Garapiá | IPR Juriti/SM 98012 | DDPA | Mesoamerican | Carioca | 2013 |
| BRS Campeiro | Mutation induction program for the cultivar Corrente by gama radiation | EMBRAPA | Mesoamerican | Black | 2003 |
| BRS Esplendor | CB911863/AN9123293 | EMBRAPA | Mesoamerican | Black | 2007 |
| IPR Graúna | EP 173/2/Rio Iguaçu/Great Northern Nebraska 1 sel#27/3/ Rio Tibagi/Cornell 49242/4/ IAPAR BAC 25/5/IAPAR BAC 26 | IDR | Mesoamerican | Black | 2002 |
| BRS Valente | (Emgopa 201-Ouro/Ônix)//AN 512586) | EMBRAPA | Mesoamerican | Black | 2001 |
| IPR Tiziu | IAPAR LP91-117/IAC Una | IDR | Mesoamerican | Black | 2007 |
| IPR Uirapurú | BAC29/PR1711/3/NEP2/2/ Puebla1731Capijao | IDR | Mesoamerican | Black | 2000 |
| Fepagro Triunfo | FT86-105/FT120//BR FEPAGRO 44 Guapo Brilhante | DDPA | Mesoamerican | Black | 2013 |
| BRS Expedito | CNF 5491/FT Tarumã | EMBRAPA | Mesoamerican | Black | 2006 |
| IPR Tuiuiú | LP96-72/Xamego | IDR | Mesoamerican | Black | 2010 |
| Guapo Brilhante (BR FEPAGRO 44) | XAN 125/[BAT 336 (A83/ICA Pijao)] | EMBRAPA | Mesoamerican | Black | 1995 |
| BRS Esteio | FT85-113/POT 51 | EMBRAPA | Mesoamerican | Black | 2012 |
| IAC Netuno | IAC Una/IPR Tuiuiú | IAC | Mesoamerican | Black | 2016 |
| Fepagro 26 | Selection in the cultivar Guapo Brilhante (BR FEPAGRO 44) | DDPA | Mesoamerican | Black | 2006 |

[1]Breeding Program: Embrapa – Brazilian Agricultural Research Corporation; DDPA - Department of Diagnosis and Agricultural Research of the Secretariat of Agriculture, Livestock, and Rural Development of the State of Rio Grande do Sul; IDR - Rural Development Institute of Paraná; EPAGRI - Agricultural Research and Rural Extension Corporation of Santa Catarina; IAC - Agronomic Institute of Campinas.

The experimental design was a randomized block with three replicates. Each block contained 25 experimental plots, and the common bean cultivars were randomized within each block. Each plot consisted of four rows, each 4 m long and spaced 0.5 m apart, totaling 8 m². The two central rows were considered the usable area (4 m²).

### *Experimental site, growing seasons, and field management*

The grains of the common bean cultivars were produced in field experiments conducted in an area of the Federal University of Santa Maria (UFSM), located in Santa Maria, Rio Grande do Sul, Brazil. The geographical coordinates of the experimental area are 29°42' S, 53°43' W, and 95 m altitude. The climate is humid subtropical (Alvares et al., 2013), with an average annual temperature of 18 °C and annual precipitation of 1,800 mm (Instituto Nacional de Meteorologia [INMET], 2021).

Four experiments were undertaken in different growing seasons: 2019 rainy, 2020 rainy, 2021 dry, and 2021 rainy season. The rainy season is the preferred period for common bean cultivation in the region (October to January), while the dry season (February to May) is less favorable due to lower temperatures and higher precipitation in the days preceding the harvest.

Cultivation was carried out in a typic alitic Argisol, Hapludalf soil, prepared using the conventional cultivation system. The soil had the following chemical composition in 2019: pH ($H_2O$): 6.7, organic matter: 2.0%, K: 60.0 mg dm$^{-3}$, P: 12.3 mg dm$^{-3}$, Ca: 5.6 cmol dm$^{-3}$, Mg: 3.0 cmol dm$^{-3}$, and Zn: 1.0 mg dm$^{-3}$. Based on this report, the quantities of fertilizers needed to correct soil fertility were calculated. Soil analysis was also carried out in 2020 and 2021 to determine the fertilizer doses to be applied in the remaining growing seasons.

Management practices were standardized and uniform across all experiments to provide ideal conditions for plant development. Control of invasive plants and insects, as well as irrigation, was conducted in accordance with technical recommendations for common bean cultivation in the region (Comissão Técnica Sul Brasileira de Feijão [CTSBF], 2012).

The harvest was performed when the plants exhibited at least 90% dry pods. The entire grain harvesting and threshing process was manual to minimize mechanical damage and the mixing of grains from different cultivars. Grain moisture was standardized at 13% for all cultivars.

### *Commercial grain quality*

The commercial quality of the grains was analyzed based on ten traits: three related to grain color, four indicating grain size, and three associated with cooking quality. Grain color was quantitatively evaluated by defining the values of L*, a*, and b* using a portable colorimeter. Samples of 50 g of grains/replicate were used to assess the L* (0 to 100; black to white), a* (-60 to 60; green to red), and b* (-60 to 60; blue to yellow) values, with each measurement taken in triplicate.

Grain size indicators (length, width, and thickness) were obtained with a digital caliper on 10 random common bean grains/replicate. The length (parallel to the hilum), width (from the hilum to its opposite side), and thickness (perpendicular to the length and width) were measured. Mass of 100 grains was ascertained by weighing 100 random grains in triplicate/replicate.

Traits associated with cooking quality (normal grains, water absorption, and cooking time) were analyzed using 25 randomly selected grains/replicate, which were previously weighed to determine their dry weight. Subsequently, 50 mL of distilled water were added, and the grains were soaked for 8 h at room temperature (20 ± 2 ºC). After soaking, the water was drained, and the grains were superficially dried with paper towels to obtain the wet weight. Normal grains, defined as those that absorbed water, were counted and expressed as a percentage. Water absorption was calculated using the following formula:

$$WA = [(WW - DW) / DW] \times 100 \qquad (1)$$

WA = water absorption

WW = wet weight of grains

DW = dry weight of grains.

A Mattson cooker with 25 metal plungers was used to determine cooking time. The device features a support plate at the base with 25 holes, onto which the common bean grains were arranged. Metal plungers were positioned above each grain, and the device was then placed inside a 7-L pan containing 3 L of boiling distilled water. The cooking process was carried out on a domestic stove, and each grain was considered cooked when the plunger dropped and pierced the grain. The time for each plunger to drop was recorded, and the average dropping time of the first 13 plungers was considered the cooking time for each sample.

### *Mineral concentration*

The concentrations of potassium, phosphorus, calcium, magnesium, iron, zinc, and copper were quantified in raw grains. To this end, a sample of 50 g of grains/replicate was ground in a micromill. A 0.5 g sub-sample of the fine powder was used for acid digestion of organic matter with nitric acid and perchloric acid, following the methodology described by Miyazawa et al. (2009). Mineral concentrations were determined using an atomic absorption spectrophotometer, except for potassium and phosphorus, which were measured with a flame photometer and an optical emission spectrophotometer, respectively.

### *Statistical analyses*

Data on normal grains (%), water absorption (%), and cooking time (min) did not meet the normality assumption and were thus transformed. For normal grains and water absorption, the following equation was used:

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

in which $x$ is the original value in percentage terms.

Cooking time was converted to seconds (s). All data transformations were performed in Microsoft® Office Excel. The transformed data, along with data from other evaluated traits, were subjected to analysis of variance for each individual experiment. Statistical analyses were performed using Genes software (Cruz, 2016).

Hartley's maximum F test was applied to verify the homogeneity of residual variances for the 17 traits examined in the four experiments. Subsequently, a combined analysis of variance was conducted, treating the source of variation 'cultivar' and the mean as fixed effects and other model parameters as random effects. In the combined analysis of variance, the phenotypic variation was partitioned into genotype, environment, and genotype × environment interaction for all traits evaluated. The Scott-Knott test was used to group the means for each trait analyzed individually in the common bean cultivars.

Genetic divergence (principal components) and selection index (multiplicative index) analyses were performed under weak multicollinearity (condition number < 100), adopting the classes defined by Montgomery et al. (2021). For this, multicollinearity diagnostics was implemented based on the phenotypic correlation matrix from the combined analysis of variance. To obtain severe multicollinearity (condition number > 1000), traits to be excluded were identified based on the criteria recommended by Cruz and Carneiro (2003).

Principal component and multiplicative index analyses utilized residual variance and covariance matrices from the combined analysis of variance. The traits contributing most to total variation were identified using principal components with standardized means. Additionally, a scatterplot was created based on the scores of the first two principal components.

Multiplicative index analysis was performed as described by Subandi et al. (1973). To select the three light-grain common bean cultivars (carioca and cranberry) with the greatest commercial grain quality and mineral concentration, emphasis was placed on the lowest values for cooking time and the highest values for other traits. To identify the three superior dark-grain (black) cultivars, selection was aimed at lower values of L* and cooking time, along with higher values for other traits. This strategy made it possible to select the six parents with multiple favorable traits.

## Results and Discussion

### *Analysis of variance and multicollinearity diagnostics*

Heterogeneous residual variances were found in the four experiments only for normal grains, mass of 100 grains, and iron concentration. For these three traits, the degrees of freedom for error and the genotype × environment interaction were adjusted using Genes software (Cruz, 2016). After achieving homogeneous residual variances for all evaluated traits, a combined analysis of variance was implemented.

Considering the source of variation ‘genotype’, no significant differences were found for normal grains, water absorption, or potassium and phosphorus concentrations (Table 2). However, for the other traits, the F test was significant at the 5% probability level, indicating genetic variability among common bean cultivars released in Brazil over the past

40 years for most commercial grain quality traits and mineral concentrations. Genotype was the main contributor to the phenotypic variance of L*, a*, b*, length, width, thickness, and mass of 100 grains, indicating that these traits were minimally influenced by the environment.

Broad genetic diversity has been described in common bean genotypes for grain color quantitatively analyzed (Ribeiro et al., 2019, 2023c), grain size (Boros & Wawer, 2018; Rana et al., 2015), cooking quality (Berry et al., 2020; Rivera et al., 2018), and mineral concentration (Delfini et al., 2020; McClean et al., 2017). The existence of genetic variability enables the selection of parents with favorable traits to be included in directed crosses. Crossing between parents of the same grain type, such as cranberry × cranberry, carioca × carioca, and black × black, tends to increase intragroup variability. This enhances the efficiency of developing new common bean cultivars with grain types to meet market demand. Nonetheless, crossing between parents of different gene pools (cranberry × carioca and cranberry × black) is rarely performed due to the greater likelihood of incompatibilities.

**Table 2**

**Combined analysis of variance containing the degrees of freedom (DF), mean squares (MS), phenotypic variation (PV, %), mean, coefficient of experimental variation (CEV%), and selective accuracy (SA) for the following traits: L* value (L), a* value (a), b* value (b), grain length (Length, mm), grain width (Width, mm), grain thickness (Thick, mm), mass of 100 grains (M100G, g), normal grains (NG, %), water absorption (Abs, %), cooking time (CT, min:s), and 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 25 common bean cultivars evaluated in four experiments carried out between 2019 and 2021**

| Trait | | Block/E DF = 8 | Genotype (G) DF = 24 | Environment (E) DF = 3 | G × E DF = 72 | Error DF = 192 | Mean | CEV (%) | SA |
|---|---|---|---|---|---|---|---|---|---|
| L | MS | 1.33 | 3387.53* | 72.66* | 7.28* | 1.07 | 37.73 | 2.75 | 1.00 |
| | PV | 0.01 | 98.83 | 0.26 | 0.64 | 0.25 | | | |
| a | MS | 0.19 | 149.39* | 22.23* | 2.25* | 0.22 | 4.90 | 9.54 | 0.99 |
| | PV | 0.04 | 92.94 | 1.73 | 4.20 | 1.09 | | | |
| b | MS | 0.20 | 1033.70* | 20.79* | 1.45* | 0.19 | 7.23 | 6.01 | 1.00 |
| | PV | 0.01 | 99.18 | 0.25 | 0.42 | 0.15 | | | |
| Length | MS | 0.15 | 10.94* | 1.53* | 0.32* | 0.11 | 10.89 | 3.06 | 0.98 |
| | PV | 0.38 | 83.98 | 1.47 | 7.37 | 6.80 | | | |
| Width | MS | 0.04 | 0.86* | 3.55* | 0.11* | 0.03 | 6.79 | 2.63 | 0.93 |
| | PV | 0.68 | 45.06 | 23.30 | 17.59 | 13.38 | | | |
| Thick | MS | 0.05 | 0.71* | 1.06* | 0.08* | 0.03 | 4.84 | 3.59 | 0.94 |
| | PV | 1.24 | 53.16 | 9.96 | 17.52 | 18.11 | | | |

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|---|---|---|---|---|---|---|---|---|---|
| M100G | MS | 4.52 | 218.16* | 242.11* | 12.53* | 1.93 | 24.68 | 5.63 | 0.97 |
| | PV | 0.50 | 72.00 | 9.99 | 12.41 | 5.10 | | | |
| NG | MS | 0.27 | 0.17$^{ns}$ | 1.52* | 0.20$^{ns}$ | 0.14 | 97.27 | 3.77 | 0.00 |
| | PV | 6.95 | 13.04 | 14.37 | 25.71 | 39.93 | | | |
| Abs | MS | 1.60 | 2.15$^{ns}$ | 27.86* | 1.40* | 0.50 | 92.84 | 7.36 | 0.59 |
| | PV | 3.69 | 14.93 | 24.13 | 29.22 | 28.02 | | | |
| CT | MS | 125960.92 | 98763.91* | 970454.70* | 40635.58* | 20678.70 | 17:48 | 13.46 | 0.77 |
| | PV | 7.64 | 17.98 | 22.08 | 22.19 | 30.11 | | | |
| K | MS | 10.08 | 4.84$^{ns}$ | 66.36* | 3.57* | 2.03 | 11.97 | 11.91 | 0.51 |
| | PV | 7.73 | 11.15 | 19.08 | 24.66 | 37.38 | | | |
| P | MS | 2.02 | 0.17$^{ns}$ | 15.71* | 0.29* | 0.18 | 4.51 | 9.55 | 0.00 |
| | PV | 13.05 | 3.32 | 38.08 | 16.78 | 28.77 | | | |
| Ca | MS | 0.03 | 0.29* | 3.93* | 0.06* | 0.03 | 1.14 | 15.19 | 0.89 |
| | PV | 0.88 | 24.25 | 40.38 | 14.76 | 19.74 | | | |
| Mg | MS | 1.62 | 0.06* | 16.28* | 0.02$^{ns}$ | 0.02 | 1.43 | 8.80 | 0.85 |
| | PV | 19.74 | 2.20 | 74.49 | 1.15 | 2.42 | | | |
| Fe | MS | 192.37 | 254.76* | 2291.62* | 114.50$^{ns}$ | 91.40 | 53.46 | 17.88 | 0.74 |
| | PV | 4.74 | 18.81 | 21.15 | 19.02 | 36.28 | | | |
| Zn | MS | 22.58 | 26.92* | 1117.03* | 9.53$^{ns}$ | 7.39 | 24.55 | 11.08 | 0.80 |
| | PV | 2.87 | 10.28 | 53.33 | 10.92 | 22.59 | | | |
| Cu | MS | 3.40 | 2.04* | 127.11* | 0.47$^{ns}$ | 0.53 | 7.01 | 10.41 | 0.88 |
| | PV | 4.58 | 8.26 | 64.25 | 5.71 | 17.20 | | | |

* Significant by F test at 0.05 probability. $^{ns}$ Not significant.

As regards the source of variation 'environment', a significant effect was observed for all traits. Similarly, grain quality traits (Cichy et al., 2019; Delfini et al., 2017) and mineral concentration (Delfini et al., 2021; McClean et al., 2017) determined in common bean genotypes have shown different responses across multiple environments. These results suggest that climatic conditions, biotic factors, management practices, and the physico-chemical characteristics of the soil can influence commercial grain quality and mineral concentration in common bean genotypes.

A significant genotype × environment interaction effect was noted for all traits except for normal grains and the concentrations of magnesium, iron, zinc, and copper. This observation shows that most traits exhibited variation when common bean cultivars were cultivated across different years and growing seasons, reinforcing findings from previous studies conducted in distinct environments (Dias et al., 2021; McClean et al., 2017). In this case, the selection of superior parents for commercial grain quality and high mineral concentrations will be specific for each environment. This makes it difficult to define which controlled crosses will be carried out by the breeding program.

For common bean, previous studies have shown that the use of average data from the four experiments is a strategic approach to more effectively identify superior parents with favorable grain quality and mineral traits (Delfini et al., 2020; Ribeiro et al., 2023a,b). Delfini et al. (2020) also observed a significant genotype × interaction for the minerals in common bean accessions from the Rural Development Institute of Paraná, Brazil. However, their genetic diversity analysis was based on average data from four experiments. Similarly, Ribeiro et al. (2023a) demonstrated that using a database of four experiments in cluster analyses provides greater detail about the differences between common bean genotypes for grain physical quality and minerals, allowing for more accurate identification of promising parents for use in controlled crosses. Additionally, average data from the four experiments proved suitable for increasing the efficiency of simultaneous selection for grain quality traits and mineral concentration in common bean lines (Ribeiro et al., 2023b). In the present study, the partitioning of the phenotypic variation revealed that the genotype × environment interaction accounted for the largest portion of the variance only for water absorption. Therefore, principal component and multiplicative index analyses were implemented using average data from the four field experiments. This methodology made it possible to accurately interpret the genetic diversity of common bean cultivars in relation to commercial grain quality traits and minerals and to select superior parents for use in crossing blocks.

For normal grains, neither the effect of genotype nor genotype × environment interaction was significant, which led to the exclusion of this trait from the multicollinearity diagnostic analysis. From the analysis of 16 traits remaining, a condition number of 6,798.28 was obtained, indicating severe multicollinearity as defined by Montgomery et al. (2021). After the exclusion of traits causing multicollinearity effects (a*, b*, length, and thickness) weak multicollinearity was achieved. The identification of these traits was guided by the analysis of highly correlated traits, traits with a greater weight in the last eigenvectors, and traits with a variance inflation factor > 10, as recommended by Cruz and Carneiro (2003).

The set of 12 variables (L*, width, mass of 100 grains, water absorption, cooking time, and concentrations of potassium, phosphorus, calcium, magnesium, iron, zinc, and copper) was used for principal component and multiplicative index analyses. This approach allowed for a considerable reduction of the undesirable effects of multicollinearity in these analyses.

### *Genetic divergence for commercial grain quality traits and mineral concentration*

The first three principal components accounted for 66.28% of the total variation (Table 3). The first principal component alone explained 32.76% of this variation, with mass of 100 grains, width, and calcium concentration being the traits that most contributed to differentiating the common bean cultivars. In the second principal component (19.97% of the variation), the most relevant traits were iron and copper concentrations. The third principal component and subsequent ones had little contribution to the total variation, thereby diminishing the importance of traits with higher eigenvalues in these components for distinguishing between cultivars. Consequently, a scatterplot was created based on the scores of the first two principal components (Figure 1).

**Table 3**

**Estimation of eigenvalues (Root and % cumulative [Cum.]) and relative importance of the traits L* value (L), grain width (Width, mm), mass of 100 grains (M100G, g), water absorption (Abs), cooking time (CT), and concentrations of potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and copper (Cu) obtained in each principal component (PC) to estimate genetic dissimilarity among 25 common bean cultivars evaluated in four experiments carried out between 2019 and 2021**

| PC | Root (%) | Cum. (%) | L | Width | M100G | Abs | CT | K | P | Ca | Mg | Fe | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PC1 | 32.76 | 32.76 | 0.37 | 0.40 | 0.46 | 0.10 | 0.08 | -0.30 | 0.08 | -0.40 | -0.29 | -0.16 | 0.27 | -0.16 |
| PC2 | 19.97 | 52.73 | -0.32 | 0.25 | 0.07 | -0.28 | 0.34 | -0.16 | 0.09 | 0.14 | -0.26 | 0.54 | 0.23 | 0.41 |
| PC3 | 13.54 | 66.28 | 0.07 | 0.09 | -0.10 | 0.06 | -0.50 | 0.49 | 0.53 | -0.14 | -0.13 | 0.04 | 0.28 | 0.29 |
| PC4 | 10.88 | 77.16 | -0.05 | 0.14 | 0.22 | 0.62 | 0.32 | -0.01 | 0.44 | 0.21 | 0.31 | -0.02 | -0.25 | 0.18 |
| PC5 | 6.03 | 83.19 | -0.24 | -0.06 | 0.05 | -0.36 | 0.17 | 0.08 | 0.44 | -0.10 | -0.42 | -0.29 | -0.53 | -0.16 |
| PC6 | 5.81 | 89.00 | 0.09 | 0.15 | 0.10 | -0.37 | 0.24 | 0.27 | 0.26 | 0.34 | 0.36 | -0.03 | 0.37 | -0.49 |
| PC7 | 3.20 | 92.19 | -0.06 | 0.03 | 0.23 | -0.35 | 0.16 | 0.17 | -0.12 | -0.45 | 0.51 | -0.26 | -0.05 | 0.46 |
| PC8 | 2.61 | 94.80 | -0.12 | -0.55 | 0.06 | -0.01 | 0.04 | -0.36 | 0.21 | 0.19 | -0.07 | -0.45 | 0.46 | 0.22 |
| PC9 | 1.90 | 96.70 | 0.67 | -0.01 | -0.23 | -0.32 | -0.07 | -0.37 | 0.26 | 0.17 | 0.15 | 0.12 | -0.25 | 0.23 |
| PC10 | 1.76 | 98.46 | 0.42 | -0.33 | -0.18 | 0.14 | 0.59 | 0.43 | -0.10 | -0.13 | -0.27 | 0.05 | 0.10 | 0.10 |
| PC11 | 1.04 | 99.50 | 0.08 | 0.47 | -0.12 | -0.02 | 0.02 | 0.17 | -0.29 | 0.48 | -0.23 | -0.52 | -0.02 | 0.29 |
| PC12 | 0.49 | 100.00 | 0.18 | -0.29 | 0.74 | -0.09 | -0.22 | 0.22 | -0.16 | 0.33 | -0.13 | 0.17 | -0.17 | 0.10 |

Mass of 100 grains has been used as an efficient morphological descriptor to detect dissimilarities between common bean genotypes (Hegay et al., 2014; Savić et al., 2019). Among the minerals, sulfur (Delfini et al., 2020; McClean et al., 2017) and calcium (Rivera et al., 2018; Yeken et al., 2018) have stood out as those with the greatest contribution to genetic diversity in common bean accessions. Zinc (Delfini et al., 2020; Yeken et al., 2018) and iron (Martins et al., 2022) have been reported to be the trace elements most indicated to classify common bean genotypes in relation to nutritional quality. In the current study, mass of 100 grains and iron concentration were the most effective descriptors for differentiating common bean cultivars concerning commercial grain quality and mineral concentration. The differences observed in relation to the most effective mineral for analyzing genetic divergence among common bean accessions are justified by the genetic diversity of the germplasm, the environment evaluated (particularly, meteorological variables and chemical and physical composition of the soil), and the number of elements determined. The environment was the greatest contributor to the variance for the concentrations of phosphorus, calcium, magnesium, zinc, and copper (Table 2), demonstrating lower efficiency in phenotypic selection for these minerals in the cultivars evaluated. These results reinforce the need to identify more effective descriptors for use in local bean breeding programs aimed at genetic biofortification.

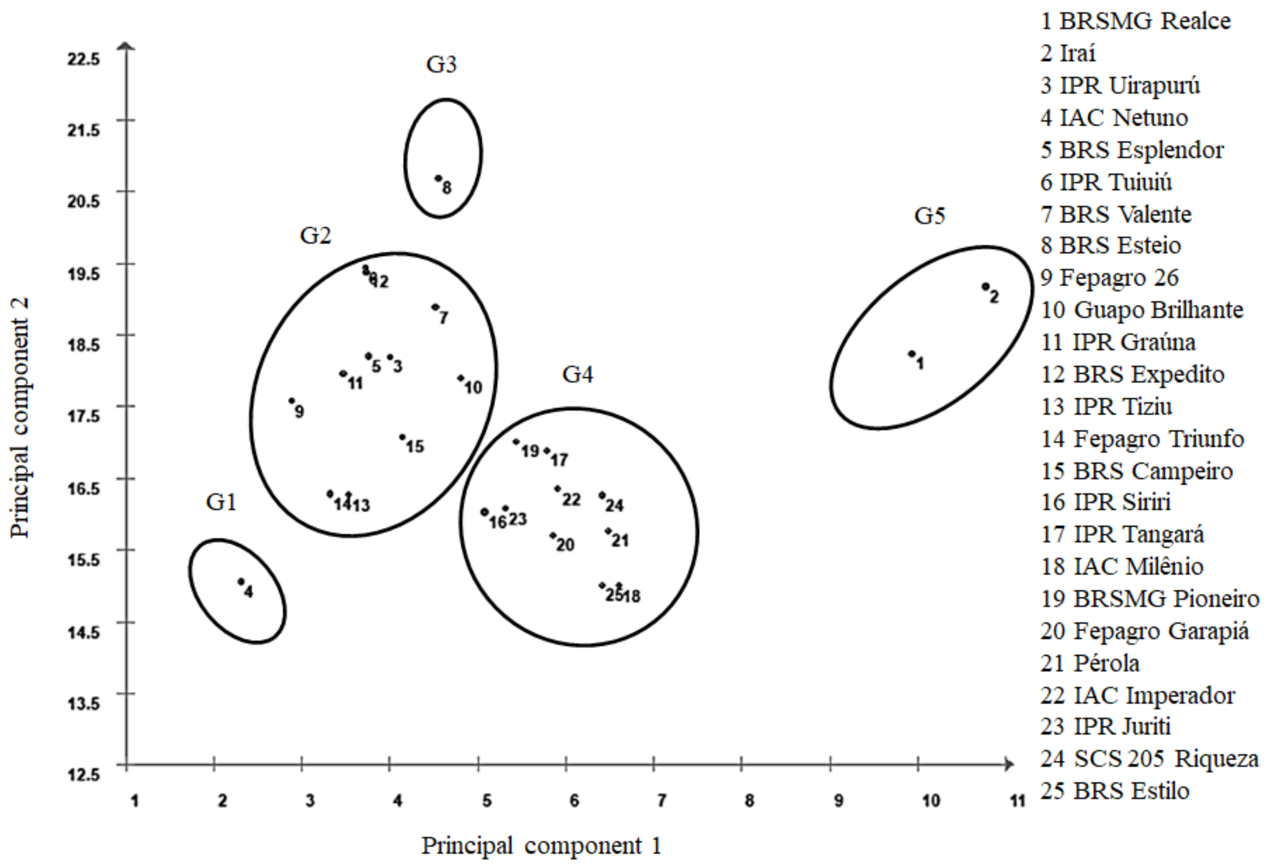


**Figure 1.** Scatter plot obtained from the commercial grain quality traits and mineral concentration of 25 common bean cultivars for the first two principal components.

Principal component analysis led to the formation of five distinct groups of common bean cultivars, differing in commercial grain quality and mineral concentration (Figure 1). Groups 1, 2, and 3 consisted of black grain cultivars. Group 1, comprised solely of cultivar IAC Netuno, was notable for having the narrowest grain width (Table 4) and the highest magnesium concentration (Table 5). Group 3 contained cultivar BRS Esteio

(Figure 1), which exhibited the highest iron concentration among the evaluated cultivars (Table 5), while Group 2 encompassed the remaining black grain cultivars (Figure 1). Similarly, black grain lines were classified into distinct groups based on agronomic traits, grain size, and mineral concentration through the use of principal component analysis (Maziero et al., 2017). Such findings demonstrate the efforts of Brazil's breeding programs to improve the commercial grain quality and mineral concentration of black common bean cultivars.

However, black common bean cultivars released in Brazil over the past 40 years have shown very uniform grain color and dimensions, with mass of 100 grains ≥ 20.4 g, fast cooking (≤ 21 min and 23 s) (Table 4), and similar mineral concentration (Table 5), indicating a narrow genetic base. Only IAC Netuno and BRS Esteio stood out for magnesium and iron concentrations, respectively, distinguishing themselves from the remaining cultivars of this grain type. Both cultivars have distinct genealogies: IAC Netuno resulted from the FT85-113 × POT 51 cross and BRS Esteio originated from the IAC Una × IPR Tuiuiú cross (Table 1). The hypothesis is that the main focus of common bean breeding programs remains increasing grain yield and selecting grain types with greater market acceptance, with little investment in genetic biofortification. As a consequence, low genetic divergence has been observed for grain quality traits and minerals among cultivars of the same grain type.

Group 4 clustered all carioca grain cultivars (Figure 1), indicating genetic similarities among the cultivars of this grain type. These cultivars were characterized by slightly reddish grains (intermediate a* values), more yellowish hues (higher b* values), and a mass of 100 grains that was intermediate compared to black and cranberry grains (Table 4). Brazilian breeding programs for carioca common bean have applied high selection pressure to develop lines with larger grains featuring slow darkening and reduced cooking time (Chiorato et al., 2010). This selection strategy might have resulted in a narrow genetic base for commercial grain and nutritional quality traits in carioca beans. The results obtained in this study show that carioca grain cultivars released for cultivation in Brazil over the past 40 years have great genetic similarity to commercial grain quality and minerals.

Group 5 consisted of the cranberry grain cultivars BRSMG Realce and Iraí (Figure 1), distinguished by their redder (higher a* values) and slightly yellow grains (intermediate b* values), higher mass of 100 grains, and the largest dimensions for grain length, width, and thickness (Table 4). The differentiation of cranberry grain cultivars from other Andean and Mesoamerican cultivars was primarily based on grain color (L*, a*, and b* values) and size (Kläsener et al., 2022), using canonical variables. Cranberry grain cultivars possess high commercial grain quality, which can contribute to broadening the area cultivated in Brazil with this grain type. To achieve this, it is necessary to develop new cranberry bean cultivars with greater genetic diversity for minerals, because the cultivars BRSMG Realce and Iraí exhibit great genetic similarity to these elements, despite displaying different genealogies (Table 1).

**Table 4**
**Mean values obtained for L* value (L), a* value (a), b* value (b), grain length (Length, mm), grain width (Width, mm), grain thickness (Thick, mm), mass of 100 grains (M100G, g), normal grains (NG, %), water absorption (Abs, %), and cooking time (CT, min:s) of 25 common bean cultivars evaluated in four experiments carried out between 2019 and 2021**

| Cultivar | L | a | b | Length | Width | Thick | M100G | NG | Abs | CT |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Cranberry grain | | | | | |
| BRSMG Realce | 54.4c | 10.0b | 15.3e | 13.4b | 7.2b | 5.5a | 37.0b | 96.2$^{ns}$ | 90.8a | 19:51a |
| Iraí | 53.8c | 10.7a | 15.8d | 14.1a | 7.5a | 5.4b | 38.2a | 99.6 | 99.6a | 20:27a |
| Mean | 54.1 | 10.3 | 15.6 | 13.8 | 7.4 | 5.4 | 37.6 | 97.9 | 95.2 | 20:09 |
| | | | | | Carioca grain | | | | | |
| BRSMG Pioneiro | 54.0c | 7.6e | 15.8d | 10.5e | 6.7e | 4.6e | 23.0f | 98.6 | 104.1a | 18:50a |
| IPR Siriri | 54.2c | 8.4c | 17.1b | 10.7d | 6.7e | 4.6e | 22.8f | 95.4 | 76.9b | 16:49b |
| SCS 205 Riqueza | 54.4c | 8.5c | 17.4b | 11.1c | 6.9d | 5.0c | 25.5d | 98.2 | 93.3a | 17:49b |
| IAC Imperador | 54.9b | 8.4c | 17.1b | 10.9d | 6.8d | 4.9c | 24.6e | 99.6 | 96.6a | 17:21b |
| IPR Juriti | 55.0b | 8.1c | 17.8a | 11.2c | 6.7e | 4.9c | 26.1d | 98.2 | 97.9a | 17:34b |
| Pérola | 55.2b | 8.3c | 17.1b | 11.2c | 7.1c | 4.9c | 27.0c | 99.2 | 98.9a | 16:38b |
| BRS Estilo | 55.3b | 7.7e | 16.1c | 10.8d | 6.8e | 5.0c | 24.9e | 99.9 | 100.5a | 15:09b |
| IAC Milênio | 55.3b | 7.9d | 17.1b | 11.2c | 6.8d | 4.9c | 25.2e | 99.2 | 104.4a | 16:04b |
| IPR Tangará | 55.4b | 7.4e | 16.2c | 11.0c | 6.9d | 5.0c | 25.6d | 98.6 | 93.5a | 17:08b |
| Fepagro Garapiá | 56.3a | 7.9d | 17.4b | 10.9d | 6.6f | 4.8d | 24.6e | 96.7 | 92.9a | 16:29b |
| Mean | 55.0 | 8.0 | 16.9 | 11.0 | 6.8 | 4.9 | 24.9 | 98.4 | 95.9 | 16:59 |
| | | | | | Black grain | | | | | |
| BRS Campeiro | 22.7d | 1.5h | -1.2f | 10.9d | 6.9d | 4.8d | 24.7e | 99.6 | 97.2a | 18:29b |
| BRS Esplendor | 22.6d | 2.6f | -1.5f | 10.6d | 6.7e | 4.4f | 21.3g | 89.9 | 75.7b | 16:42b |
| IPR Graúna | 22.3d | 1.7h | -1.5f | 10.2f | 6.5f | 4.6e | 20.6g | 96.5 | 94.6a | 16:34b |
| BRS Valente | 22.0e | 2.0g | -1.7f | 10.4e | 7.0c | 4.5f | 21.8g | 96.2 | 86.1b | 16:49b |
| IPR Tiziu | 22.0e | 1.3i | -1.4f | 10.1f | 6.5f | 4.5f | 21.2g | 99.2 | 98.7a | 17:37b |
| IPR Uirapurú | 21.8e | 1.4i | -1.3f | 10.4e | 6.8e | 4.8d | 23.7e | 96.2 | 86.5b | 17:47b |
| Fepagro Triunfo | 21.8e | 2.4f | -1.7f | 10.4e | 6.5f | 4.6e | 22.1f | 97.4 | 93.7a | 17:35b |
| BRS Expedito | 21.7e | 1.6h | -1.5f | 10.8d | 6.9d | 4.8d | 24.5e | 98.2 | 100.7a | 17:05b |
| IPR Tuiuiú | 21.7e | 1.2i | -1.5f | 10.1f | 6.8d | 4.8d | 22.5f | 94.8 | 85.2b | 20:01a |
| Guapo Brilhante | 21.7e | 1.3i | -1.3f | 10.3e | 6.5f | 4.9c | 22.8f | 93.8 | 80.3b | 17:38b |
| BRS Esteio | 21.6e | 1.1i | -1.5f | 10.2f | 6.9d | 4.8d | 23.5f | 94.5 | 83.0b | 21:23a |
| IAC Netuno | 21.5e | 1.6h | -1.3f | 10.6e | 6.3g | 4.9c | 23.3f | 99.2 | 99.5a | 20:00a |
| Fepagro 26 | 21.5e | 1.6h | -1.7f | 9.9f | 6.5f | 4.7e | 20.4g | 97.1 | 94.6a | 17:13b |
| Mean | 21.9 | 1.6 | -1.5 | 10.4 | 6.7 | 4.7 | 22.5 | 96.4 | 90.5 | 18:04 |

*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 5**
**Mean values obtained for 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 25 common bean cultivars evaluated in four experiments carried out between 2019 and 2021**

| Cultivar | K | P | Ca | Mg | Fe | Zn | Cu |
|---|---|---|---|---|---|---|---|
| | | | Cranberry grain | | | | |
| BRSMG Realce | 10.7b | 4.5a | 0.9d | 1.3d | 50,0b | 26.4a | 6.7c |
| Iraí | 10.8b | 4.7a | 0.8d | 1.3d | 52,5b | 26.8a | 7.0b |
| Mean | 10.7 | 4.6 | 0.8 | 1.3 | 51.2 | 26.6 | 6.8 |
| | | | Carioca grain | | | | |
| BRSMG Pioneiro | 11.6b | 4.5a | 1.1c | 1.4b | 53.9b | 24.6a | 7.3b |
| IPR Siriri | 13.0a | 4.6a | 1.1c | 1.4c | 47.3b | 24.5a | 6.9c |
| SCS 205 Riqueza | 11.5b | 4.4a | 1.0c | 1.4c | 51.1b | 23.3b | 6.7c |
| IAC Imperador | 11.6b | 4.4a | 1.3b | 1.4c | 53.4b | 26.1a | 6.3c |
| IPR Juriti | 12.4a | 4.4a | 1.0c | 1.5b | 52.3b | 24.6a | 7.1b |
| Pérola | 12.0a | 4.5a | 1.1c | 1.5b | 51.0b | 25.2a | 6.5c |
| BRS Estilo | 12.0a | 4.7a | 1.0c | 1.4c | 46.3b | 23.9a | 6.6c |
| IAC Milênio | 12.5a | 4.5a | 0.9d | 1.4c | 48.2b | 25.4a | 6.5c |
| IPR Tangará | 11.7b | 4.5a | 1.1c | 1.5b | 51.5b | 24.3a | 7.4b |
| Fepagro Garapiá | 11.6b | 4.4a | 1.0c | 1.4b | 52.8b | 25.3a | 6.4c |
| Mean | 12.0 | 8.0 | 1.1 | 1.4 | 50.9 | 24.7 | 6,8 |
| | | | Black grain | | | | |
| BRS Campeiro | 12.3a | 4.4a | 1.1c | 1.5b | 54.2b | 21.3b | 7.1b |
| BRS Esplendor | 12.8a | 4.4a | 1.1c | 1.4c | 58.0a | 25.7a | 7.0b |
| IPR Graúna | 12.5a | 4.5a | 1.2b | 1.4c | 54.5b | 26.0a | 7.9a |
| BRS Valente | 12.7a | 4.6a | 1.2b | 1.4c | 56.9a | 26.4a | 7.4b |
| IPR Tiziu | 12.3a | 4.5a | 1.2b | 1.4b | 51.7b | 22.3b | 6.9c |
| IPR Uirapurú | 11.7b | 4.4a | 1.2b | 1.5b | 57.4a | 24.7a | 7.2b |
| Fepagro Triunfo | 11.6b | 4.3a | 1.3a | 1.4b | 50.4b | 22.2b | 6.9c |
| BRS Expedito | 12.4a | 4.8a | 1.4a | 1.5b | 61.9a | 25.5a | 7.9a |
| IPR Tuiuiú | 12.2a | 4.5a | 1.3a | 1.5b | 61.7a | 25.3a | 7.1b |
| Guapo Brilhante | 11.0b | 4.4a | 1.0c | 1.4c | 53.1b | 24.6a | 7.1b |
| BRS Esteio | 11.0b | 4.5a | 1.4a | 1.3d | 62.6a | 24.1a | 7.2b |
| IAC Netuno | 12.4a | 4.6a | 1.4a | 1.6a | 45.9b | 22.4b | 6.5c |
| Fepagro 26 | 12.7a | 4.6a | 1.2b | 1.4c | 58.0a | 22.4b | 7.3b |
| Mean | 12.1 | 4.5 | 1.2 | 1.4 | 55.9 | 24.1 | 7,2 |

*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.

*Selection for multiple traits in light-grain parents*

When applying the multiplicative index to light-grain cultivars, high heritability ($h^2$ ≥ 68.20%) was observed solely for width, mass of 100 grains, cooking time, and the concentrations of calcium, magnesium, and copper (Table 6), considering the classifications proposed by Soltani et al. (2016). Conversely, high heritability was noted across all commercial grain quality traits, as well as for iron and zinc concentrations in carioca bean inbred lines (Martins et al., 2022). In navy bean genotypes, intermediate heritability (31 > $h^2$ < 59%) was reported for iron concentration and high heritability for zinc concentration (Mutari et al., 2022). The observed high heritability for commercial grain quality and mineral concentration in the present study indicates greater genetic variability and less environmental influence, which may increase the chances of success in the selection of superior parents.

High heritability values are associated with increased genetic variability, enhancing the likelihood of achieving significant selection gains. The greatest-magnitude genetic gain was found for cooking time (-16.29%), surpassing previous estimates for light-grain genotypes (Dias et al., 2021; Kläsener et al., 2022; Ribeiro et al., 2021, 2023c). In the current study, reduced cooking time was the main modification made by the common bean breeding programs in Brazil to carioca and cranberry grain cultivars.

The carioca grain cultivars Pérola, IPR Tangará, and IPR Juriti were selected as parents for their superior commercial grain quality traits and mineral concentrations (Table 6), outperforming the other light-grain cultivars evaluated (Tables 4 and 5). These cultivars exhibited L* ≥ 55.00 (Table 6), indicating very light grains that meet the current standards of breeding programs (Arns et al., 2018). They also showed wider grains (≥ 6.90 mm) and a mass of 100 grains ≥ 25.65 g, aligning with the selection criteria for this grain type (Carbonell et al., 2010; Pereira et al., 2021). Additionally, these cultivars demonstrated high water absorption (≥93.50%) and reduced cooking times (≤17 min and 34 s), with cooking times under 25 min being considered fast for carioca and black common bean (Santos et al., 2016). Cultivars Pérola, IPR Tangará, and IPR Juriti thus have carioca grains with high commercial quality.

However, cultivars Pérola, IPR Tangará, and IPR Juriti showed little variation in mineral concentration and relatively low values (Table 6) compared to those reported for other common bean genotypes (Delfini et al., 2017, 2021; Jan et al., 2021; McClean et al., 2017). Only cultivar IPR Juriti was notable for its potassium concentration (12.39 g $kg^{-1}$ of DM), which aligns with high concentrations typically found in common bean (Steckling et al., 2017). These results indicate that increasing mineral concentration was not a priority in the breeding of the carioca common bean cultivars evaluated in the present study. Only cultivar IPR Juriti has very light grains, fast cooking time, and high potassium concentration among the carioca bean cultivars analyzed. Cultivar IPR Juriti is recommended as a parent to be used in crossing blocks for the development of new carioca bean cultivars.

**Table 6**
**Average of the original population (Xo), average of selected cultivars (Xs), heritability ($h^2$), genetic gain (GG), and percentage of genetic gain (GG%) with simultaneous selection by the multiplicative index for the traits L* value (L), grain width (Width, mm), mass of 100 grains (M100G, g), water absorption (Abs, %), cooking time (CT, min:s), and 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) for the three light-grain and the three dark-grain common bean cultivars selected based on the evaluation of four experiments carried out between 2019 and 2021**

| Trait | SD* | Xo | Xs | h² % | GG | GG % | Pérola | IPR Tangará | IPR Juriti |
|---|---|---|---|---|---|---|---|---|---|
| Light-grain common bean cultivars selected | | | | | | | | | |
| L | HV | 54.86 | 55.19 | 0.00 | 0.00 | 0.00 | 55.23 | 55.44 | 55.00 |
| Width | HV | 6.90 | 6.91 | 80.26 | 0.01 | 0.00 | 7.12 | 6.90 | 6.72 |
| M100G | HV | 27.05 | 26.24 | 93.54 | -0.76 | -0.76 | 26.99 | 25.65 | 26.09 |
| Abs | HV | 97.98 | 97.08 | 23.69 | -0.01 | -0.01 | 98.90 | 93.50 | 97.90 |
| CT | LV | 17:31 | 17:07 | 68.20 | -16.29 | -16.29 | 16:38 | 17:08 | 17:34 |
| K | HV | 11.79 | 12.00 | 0.02 | 0.00 | 0.00 | 11.96 | 11.66 | 12.39 |
| P | HV | 4.52 | 4.49 | 0.00 | 0.00 | 0.00 | 4.53 | 4.53 | 4.43 |
| Ca | HV | 1.03 | 1.06 | 70.25 | 0.02 | 0.02 | 1.08 | 1.08 | 1.03 |
| Mg | HV | 1.41 | 1.50 | 87.17 | 0.08 | 0.07 | 1.52 | 1.47 | 1.51 |
| Fe | HV | 50.86 | 51.62 | 0.00 | 0.00 | 0.00 | 51.01 | 51.53 | 52.34 |
| Zn | HV | 25.05 | 24.69 | 19.15 | -0.07 | -0.07 | 25.18 | 24.27 | 24.62 |
| Cu | HV | 6.80 | 7.05 | 76.02 | 0.19 | 0.19 | 6.55 | 7.45 | 7.15 |
| Total gain | | | | | | 5.29 | | | |
| Traits | SD | Xo | Xs | h² % | GG | GG % | BRS Expedito | BRS Valente | IPR Tuiuiú |
| Dark-grain common bean cultivars selected | | | | | | | | | |
| L | LV | 21.92 | 21.82 | 66.44 | -0.07 | -0.30 | 21.74 | 22.00 | 21.74 |
| Width | HV | 6.68 | 6.92 | 90.61 | 0.22 | 3.23 | 6.90 | 7.03 | 6.84 |
| M100G | HV | 22.50 | 22.93 | 83.63 | 0.36 | 1.61 | 24.48 | 21.77 | 22.56 |
| Abs | HV | 91.81 | 91.30 | 36.78 | -0.00 | -0.04 | 100.70 | 85.24 | 86.12 |
| CT | LV | 18:04 | 17:58 | 47.78 | -2.73 | -0.25 | 17:05 | 16:49 | 20:01 |
| K | HV | 12.13 | 12.45 | 45.32 | 0.14 | 1.17 | 12.41 | 12.75 | 12.20 |
| P | HV | 4.50 | 4.63 | 0.00 | 0.00 | 0.00 | 4.78 | 4.64 | 4.47 |
| Ca | HV | 1.24 | 1.30 | 71.99 | 0.04 | 3.44 | 1.39 | 1.18 | 1.32 |
| Mg | HV | 1.44 | 1.44 | 79.86 | 0.00 | -0.22 | 1.47 | 1.39 | 1.46 |
| Fe | HV | 55.87 | 60.15 | 69.06 | 2.96 | 5.30 | 61.91 | 56.87 | 61.67 |
| Zn | HV | 24.08 | 25.75 | 75.26 | 1.25 | 5.19 | 25.55 | 26.38 | 25.31 |
| Cu | HV | 7.20 | 7.46 | 66.56 | 0.18 | 2.48 | 7.86 | 7.42 | 7.11 |
| Total gain | | | | | | 21.61 | | | |

* SD: Selection direction - HV: Highest value. LV: Lowest value.

*Selection for multiple traits in dark-grained parents*

In selecting dark-grain cultivars, heritability values were low ($h^2 \leq 30\%$) for phosphorus concentration, intermediate ($31 > h^2 < 59\%$) for water absorption, cooking time, and potassium concentration, and high ($h^2 \geq 60\%$) for other traits (Table 6), according to the heritability classes of Soltani et al. (2016). Different heritability classes were also observed for commercial grain quality traits (Berry et al., 2020) and mineral concentrations (Delfini et al., 2021) in common bean genotypes of different grain types. Traits with higher heritability reflect a greater contribution of genetic variance to their expression, facilitating the selection of superior common bean cultivars. The black common bean cultivars evaluated in the present study exhibit great genetic variability for L*, width, mass of 100 grains, and concentrations of calcium, magnesium, iron, zinc, and copper.

The highest genetic gain estimates in the selection for dark grains were recorded for iron (5.30%) and zinc (5.19%) concentrations (Table 6). Positive genetic gains for these minerals were also found in the selection of black grain genotypes (Ribeiro et al., 2021, 2023c) and for bean accessions of different grain classes (Saradadevi et al., 2021). In the black grain cultivars analyzed in this study, increasing the iron and zinc concentrations led to greater gains from selection in common bean breeding programs.

The application of the multiplicative index led to the selection of cultivars BRS Expedito, BRS Valente, and IPR Tuiuiú (Table 6), which distinguished themselves from other black grain cultivars in terms of multiple commercial grain quality traits and mineral concentrations (Tables 4 and 5). These three cultivars exhibited a uniform black color with an L value ≤ 22.00 (Table 6), aligning with the lightness standards used in the selection of this grain type (Ribeiro et al., 2003). Their grain widths ranged from 6.84 to 7.03 mm, and they had a mass of 100 grains ≤ 24.48 g, representing small grains (Hegay et al., 2014). Typically, the selection standard used in breeding programs for black grains is a mass of 100 grains between 25 and 30 g (Carbonell et al., 2010), as larger grains are prized for their greater expansion post-soaking and enhanced cooked yield, attributes highly valued by consumers. However, all assessed black grain cultivars had an average mass of 100 grains < 25 g across the four experiments (Table 4), indicating difficulty in increasing grain size.

Cultivars BRS Expedito, BRS Valente, and IPR Tuiuiú also excelled with high water absorption rates (≥ 85.20%), reduced cooking times (≤ 20 min and 01 s), and high potassium concentrations (≥ 12.20 g $kg^{-1}$ DM) (Table 6). For the other minerals analyzed, the black grain cultivars displayed relatively low values, akin to those observed in carioca grain cultivars. A broader range of variation in mineral concentrations has been documented in common bean genotypes evaluated in Brazil (Delfini et al., 2017, 2021), the United States (McClean et al., 2017), and India (Jan et al., 2021). For the black grain cultivars in this study, the most notable changes were increased grain darkening, shortened cooking times, and higher potassium concentrations. Cultivars BRS Expedito, BRS Valente, and IPR Tuiuiú have dark-grain, fast-cooking, and high potassium concentration and are recommended as parents to be used in crossing blocks for the development of new black bean cultivars.

## Conclusions

Common bean cultivars released in Brazil in the last 40 years show genetic diversity for commercial grain quality traits and mineral concentration.

Mass of 100 grains and iron concentration as the most effective descriptors for differentiating common bean cultivars into five distinct groups by principal components.

The cultivars IPR Juriti, BRS Expedito, BRS Valente, and IPR Tuiuiú stand out for their superior commercial grain quality and also exhibit high potassium concentration (≥ 12.00 g $kg^{-1}$ of dry matter) and will be selected as parents for use in crossing blocks.

## Acknowledgments

To the National Council for Scientific and Technological and Development (CNPq) and to the Coordination for the Improvement of Higher Education Personnel (CAPES) for financial support and scholarships.

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