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Genetics/ Original Article

Selection of common bean genotypes with higher macro- and micromineral concentrations in the grains

Abstract – The objective of this work was to evaluate the genetic variability of common bean (*Phaseolus vulgaris*) genotypes of different grain types as to macro- and micromineral concentrations, as well as to select superior genotypes by the multiplicative index. A total of 22 common bean genotypes were evaluated in experiments carried out in the dry and rainy seasons. The concentration of six minerals (potassium, phosphorus, magnesium, iron, zinc, and copper) was determined, and the multiplicative index was applied to individual and combined experiments. There was a significant effect of the genotype × environment interaction on the concentration of all minerals, and, when the genotype effect was decomposed into grain types, the genotypes differed as to the concentration of three or more minerals. There is genetic variability in the concentration of macro- and microminerals in the common bean genotypes evaluated in the dry and rainy seasons. In the combined experiments, high heritability estimates (≥ 62.60%) and a greater total genetic gain (283.59%) are observed. The multiplicative index applied to combined experiments allows the selection of superior common bean genotypes of the following grain types: red (Amendoim comprido and Light Red Kidney), cranberry ('BRS Executivo' and 'Hooter'), and carioca ('IPR Siriri'), which have high phosphorus and iron concentrations; Amendoim comprido also stands out for its high potassium concentration.

Index terms: *Phaseolus vulgaris*, combined selection, genotype × environment interaction, multiplicative index.

Seleção de genótipos de feijão com maior concentração de macro e microminerais nos grãos

Resumo – O objetivo deste trabalho foi avaliar a variabilidade genética de genótipos de feijão (*Phaseolus vulgaris*) de diferentes tipos de grãos quanto à concentração de macro e microminerais, bem como selecionar genótipos superiores pelo índice multiplicativo. Um total de 22 genótipos de feijão foi avaliado em experimentos conduzidos nas estações seca e chuvosa. A concentração de seis minerais (potássio, fósforo, magnésio, ferro, zinco e cobre) foi determinada, e o índice multiplicativo foi aplicado a experimentos individuais e combinados. Houve efeito significativo da interação genótipo x ambiente sobre a concentração de todos os minerais, e, quando o efeito de genótipo foi decomposto em tipos de grãos, os genótipos diferiram quanto à concentração de três ou mais minerais. Há variabilidade genética na concentração de macro e microminerais nos genótipos de feijão comum avaliados nas estações seca e chuvosa. Nos experimentos combinados,

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são observados altas estimativas de herdabilidade (≥ 62,60%) e maior ganho genético total (283,59%). O índice multiplicativo aplicado a experimentos combinados possibilita a seleção de genótipos de feijão superiores dos seguintes tipos de grãos: vermelho (Amendoim comprido e Light Red Kidney), rajado ('BRS Executivo' e 'Hooter') e carioca ('IPR Siriri'), que apresentam alta concentração de fósforo e ferro; Amendoim comprido também se destaca pela alta concentração de potássio.

Termos para indexação: *Phaseolus vulgaris*, seleção combinada, interação genótipo x ambiente, índice multiplicativo.

Introduction

Several common bean (*Phaseolus vulgaris* L.) grain types are produced in Brazil. Among them, the carioca (beige seed coat with brown streaks) and black grains are largely accepted in the domestic market, whereas the red and cranberry (cream seed coat with red streaks) grains are grown regionally, being important for family farming, but with good prospects for export (Ferrari & Ramos Júnior, 2015).

Recent publications have shown that mineral concentrations can vary between common bean genotypes of different grain types (Hacisalihoglu & Settles, 2013; Ribeiro et al., 2014, 2021; McClean et al., 2017; Delfini et al., 2020). The existence of genetic variability for mineral concentrations in the grains has enabled the selection of common bean lines with high concentrations of one or more minerals (Silva et al., 2012; McClean et al., 2017; Steckling et al., 2017; Ribeiro & Kläsener, 2020; Ribeiro & Mezzomo, 2020; Zanotti et al., 2020; Dias et al., 2021). This is important since the inclusion of biofortified common bean cultivars in the diet provides health benefits, especially the prevention of symptoms related to mineral deficiencies. Mineral deficiency is a public health problem that affects thousands of people worldwide, since deficiencies in potassium (K), phosphorus (P), magnesium (Mg), iron (Fe), zinc (Zn), or copper (Cu) in the human body contribute to the development of several diseases, as extensively described by McDonough & Youn (2017), Serna & Bergwitz (2020), Barbagallo et al. (2021), Dev & Babitt (2017), Zoroddu et al. (2019), and Wazir & Ghobrial (2017), respectively.

For an efficient selection of mineral-biofortified common bean lines, environmental variability must be taken into account. Considering reports of significant effects of the genotype × environment interaction on the mineral concentrations in common bean genotypes (Pereira et al., 2011; Hossain et al., 2013; Zilio et al., 2017; Ribeiro & Kläsener, 2020; Dias et al., 2021; Ribeiro et al., 2021), the selection of superior lines should not be based only on data obtained from a single experiment, which would be unrepresentative of the genetic diversity of the germplasm.

It is possible to select common bean lines with a high concentration of two or more minerals, as shown by the combined selection for minerals using different selection indices (Silva et al., 2012; Ribeiro et al., 2014; Ribeiro & Kläsener, 2020; Ribeiro & Mezzomo, 2020; Zanotti et al., 2020; Dias et al., 2021). However, no information has been found in the literature on whether environmental variability between growing seasons influences heritability, genetic gain estimates, and the selection of superior cultivars for minerals. Therefore, the present analysis will have practical implications for an efficient selection of mineral-biofortified common bean cultivars, representing an important innovation for breeding programs.

The objective of this work was to evaluate the genetic variability of common bean genotypes of different grain types as to macro- and micromineral concentrations, as well as to select superior genotypes by the multiplicative index.

Materials and Methods

Grains of the evaluated common bean genotypes were obtained from two experiments carried out in 2019 in the area of the Common Bean Breeding Program, at Universidade Federal de Santa Maria, located in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil (29º42'S, 53º49'W, at 95 m of altitude). The first experiment was sown in February, and the second in October, which correspond to the two seasons (dry and rainy, respectively) recommended for the cultivation of common bean in Southern Brazil. According to the Köppen-Geiger classification, the climate of the region is of the humid subtropical type (Alvares et al., 2013).

The soil of the area is classified as an Argissolo Alítico típico (Santos et al., 2018), i.e., a Hapludalf, which was prepared by the conventional cultivation system, with one subsoiling and two harrowing operations. The soil analysis revealed the following chemical composition: pH (H_2O) 5.9, 19.0 g kg^{-1} organic matter, 24.5 mg dm^{-3}

P, 44.0 mg dm^{-3} K, 6.8 cmol dm^{-3} Ca, 2.5 cmol dm^{-3} Mg, 517.8 mg dm^{-3} Fe, and 0.8 mg dm^{-3} Zn. The application of the following fertilizers was required: 160 kg ha^{-1} of the N-P_2O_5-K_2O (05-20-20) formula, with urea (45% nitrogen), single superphosphate (18% P_2O_5), and potassium chloride (60% K_2O), at sowing; and 40 kg ha^{-1} urea (45% nitrogen), which was divided into two rates and distributed in the stages of first trifoliate (V3) and third trifoliate (V4) leaves. No micronutrients were added to the fertilizers.

The experiment was carried out in a randomized complete block design with three replicates. Each experimental plot was formed by two 4.0 m long rows spaced 0.5 m apart, totaling 4.0 m^2 of usable area. The 22 common bean genotypes (cultivars and landraces) evaluated are of the following grain types: carioca, black, red, and cranberry (Figure 1). These genotypes are representative of the Mesoamerican and Andean gene pools, characterizing the diversity of the common bean grain types most produced in Brazil.

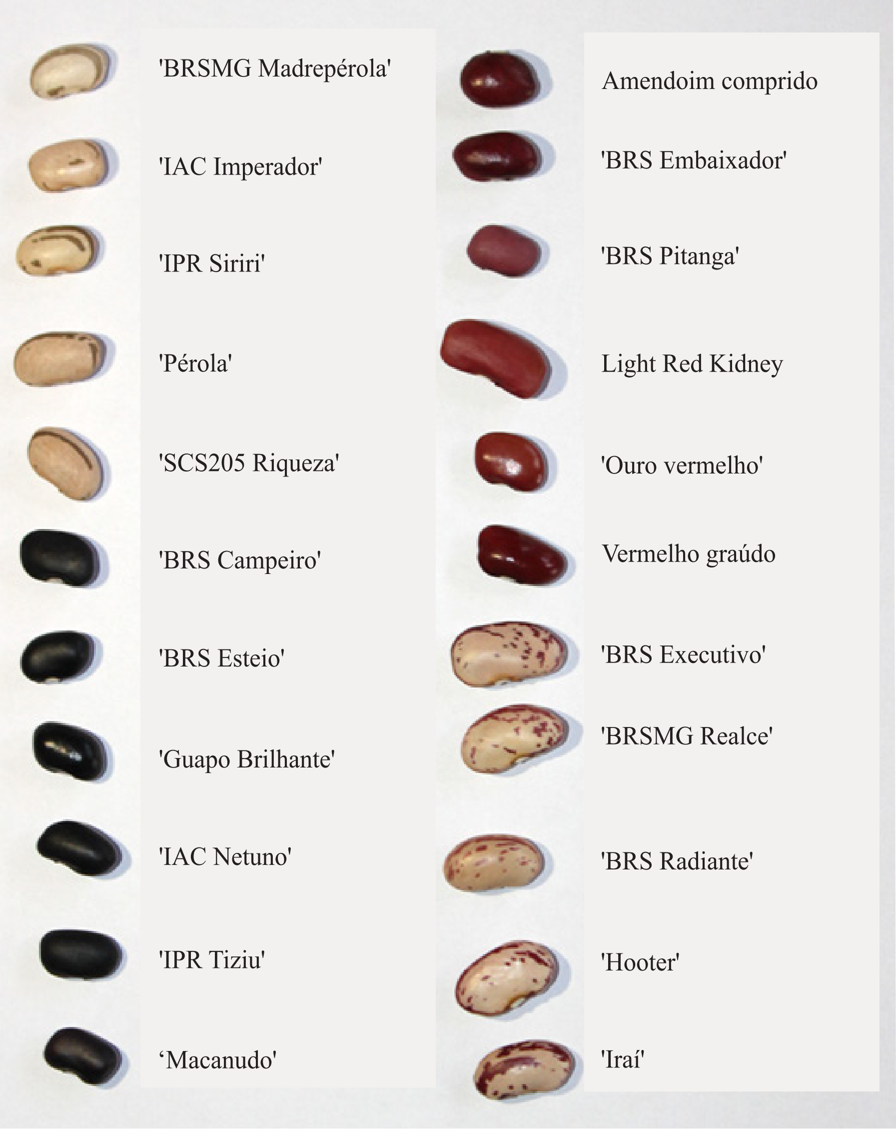

Figure 1. Evaluated common bean (*Phaseolus vulgaris*) genotypes according to their grain types: carioca, 'BRSMG Madrepérola', 'IAC Imperador', 'IPR Siriri', 'Pérola', and 'SCS205 Riqueza'; black, 'BRS Campeiro', 'BRS Esteio', 'Guapo Brilhante' ('BR FEPAGRO 44'), 'IAC Netuno', 'IPR Tiziu', and 'Macanudo' ('BR IPAGRO 1'); red, Amendoim comprido, 'BRS Embaixador', 'BRS Pitanga', Light Red Kidney, 'Ouro vermelho', and Vermelho graúdo; and cranberry, 'BRS Executivo', 'BRSMG Realce', 'BRS Radiante', 'Hooter', and 'Iraí'.

Management practices consisted of seed treatment with fungicide and insecticide, irrigation, and control of weeds and insects, which were performed following the technical recommendations for the common bean crop in Southern Brazil (CTSBF, 2012). When the pods were dry and the grains exhibited the typical color of each genotype, the plants harvested in each plot were identified and stored in a protected environment until the grains could be removed. Grain moisture was determined using a portable moisture meter and, if necessary, the grains were oven dried to reach 13% moisture. The grains were kept under refrigeration at 5ºC and 75% relative humidity until the mineral analysis.

The concentration of three macrominerals (K, P, and Mg) and three microminerals (Fe, Zn, and Cu) was determined in raw grain samples. To this end, a sample of 30 g common bean grains was randomly collected from each experimental plot. The samples were ground in a micromill until a fine and homogeneous powder was obtained. A 0.5 g aliquot of the ground sample was placed in a falcon tube to which nitric and perchloric acids were added. The acid solution was prepared, and the digestion process was performed according to the methodology described by Miyazawa et al. (2009).

K concentration was measured using a flame photometer at a wavelength of 660 nm, whereas P was determined in an optical emission spectrophotometer at a wavelength of 690 nm. Mg, Fe, Zn, and Cu were read in an atomic absorption spectrophotometer, using the indicated dilutions for each mineral and the respective wavelengths of 285.20, 248.30, 213.00, and 324.75 nm. Results for macro- and microminerals were expressed in g kg^{-1} and mg kg^{-1} dry matter (DM).

Data were subjected to individual and combined analyses of variance, and the homogeneity of residual variance was evaluated by Hartley's maximum F-test (Cruz et al., 2014). The combined analysis of variance was performed considering all effects as fixed, except experimental error, which was considered random. The genotype effect was decomposed into grain types, which allowed the evaluation of common bean genotypes within and between different grain types. The significance level was analyzed by the F-test, at 5% probability, in individual and combined analyses of variance. Means were grouped by Scott-Knott's test, at 5% probability.

The phenotypic correlation matrix obtained from the combined analysis of variance was used for multicollinearity diagnostics. Collinearity classes were analyzed according to the classification of Montgomery et al. (2012), to assess whether or not there were highly correlated traits.

The analyses of the selection index considered data from each growing season separately (2019 dry season and 2019 rainy season) and the average of both seasons (2019 dry season + 2019 rainy season) for individual and combined experiments, respectively. In each of these situations, estimates of heritability and selection gain were obtained and the five superior common bean genotypes for mineral concentrations were selected, which corresponds to a selection intensity of 22.73%. For this purpose, selection was carried out using the multiplicative index (Subandi et al., 1973) to increase the concentration of all minerals. Statistical analyses were processed using the Genes software (Cruz, 2016).

Results and Discussion

There was a significant effect of the genotype × environment interaction on all minerals (Table 1), which shows that the macro- and micromineral concentrations in the common bean genotypes varied with the growing season. Previous works confirm that the mineral concentration in common bean genotypes changed according to the growing environment (Pereira et al., 2011; Hossain et al., 2013; Zilio et al., 2017; Ribeiro & Kläsener, 2020; Dias et al., 2021; Ribeiro et al., 2021). For this reason, the environmental variability between seasons was considered in the present study, so that the selection of mineral-biofortified common bean genotypes was efficient and representative of the genetic diversity of the germplasm.

By decomposing the genotype effect into grain types, it was observed that the common bean genotypes differed for the concentration of three or more minerals. Variations in the mineral concentrations in common bean genotypes of different grain types have also been reported in the literature (Hacisalihoglu & Settles, 2013; Ribeiro et al., 2014, 2021; McClean et al., 2017; Delfini et al., 2020). These results suggest it is possible to select carioca, black, red, and cranberry common bean genotypes with a high concentration of one or more minerals. This is important because it would allow meeting the diverse nutritional needs and preferences of different consumers.

K was the macromineral found in the highest amount in the common bean grains, followed by P and Mg (Table 2), as also observed by Di Bella et al. (2016) in samples of commercial common bean grains evaluated in Italy. Furthermore, K concentration ranged from 10.13 for 'BRS Esteio' and 'Iraí' in the dry season to 15.00 g kg^{-1} DM for 'BRS Radiante' in the rainy season, which is similar to the range obtained for common bean genotypes by other authors (Hossain et al., 2013; Zilio et al., 2017; Ribeiro & Kläsener, 2020). For K concentration, the common bean genotypes were grouped into two clusters in the dry season and into three clusters in the rainy season by Scott-Knott's test; only 'BRS Radiante' of the cranberry grain type integrated the genotype group with the highest K concentration values in both growing seasons. According to the classification proposed by Steckling et al. (2017), common bean genotypes of the following grain types showed a high K concentration of ≥ 12.00 g kg^{-1} DM in both growing seasons: carioca ('IPR Siriri' and 'Pérola'), black ('BRS Campeiro', 'IAC Netuno', and 'Macanudo'), red (Amendoim comprido, 'BRS Embaixador', and Light Red Kidney), and cranberry ('BRS Radiante' and 'Hooter'). This is an indicative that including common bean genotypes of different grain types biofortified with K in the diet could provide health benefits since this nutrient helps to reduce cases of hypertension (McDonough & Youn, 2017).

In the two growing seasons, common bean genotypes of the following grain types stood out for P concentration: black ('IAC Netuno' and 'IPR Tiziu'), red (Amendoim comprido, 'BRS Pitanga', and 'Ouro vermelho'), and cranberry ('BRS Executivo'). However, all common bean genotypes exhibited a high P concentration, which was defined by Steckling et al. (2017) as ≥ 5.00 g kg^{-1} DM, except genotypes 'BRSMG Realce' and 'Hooter' in the dry season and 'IPR Siriri', 'SCS205 Riqueza', 'Guapo Brilhante', 'Macanudo', 'BRS Embaixador', and Light Red Kidney in the rainy season. A diet rich in P is beneficial considering that this nutrient is required for bone mineralization (Serna & Bergwitz, 2020). However, the inclusion of common bean genotypes of different grain types biofortified with P in diets still must be evaluated regarding protection against fractures.

The group with the highest Mg values in the dry season included a higher number of common bean genotypes of the following grain types: carioca ('BRS Madrepérola', 'IAC Imperador', 'IPR Siriri', 'Pérola', and 'SCS205 Riqueza'), black ('BRS Campeiro', 'IAC Netuno', and 'IPR Tiziu'), red ('Ouro vermelho'), and cranberry ('BRS Radiante'). In the rainy season, however, only

Table 1. Combined analysis of variance containing degrees of freedom (DF), mean squares, mean, coefficient of experimental variation (CEV), and selective accuracy for the concentrations of potassium (K), phosphorus (P), magnesium (Mg), iron (Fe), zinc (Zn), and copper (Cu) in grains of 22 common bean (*Phaseolus vulgaris*) genotypes evaluated in the dry and rainy seasons of 2019, in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil.

Source of variation	DF	Mean square					
		K	P	Mg	Fe	Zn	Cu
		(g kg^{-1} dry matter)			(mg kg^{-1} dry matter)		
Block/environment	4	0.81	0.21	0.01	1.47	16.00	1.58
Genotype (G)	21	1.61*	0.76*	0.44*	362.39*	19.83*	8.01*
Grain type (T)	3	0.90^{ns}	0.32^{ns}	0.12*	295.63*	43.69*	13.13*
G/T	18	1.73^{ns}	0.83*	0.03*	373.52*	15.86*	7.15*
T/carioca	4	1.58^{ns}	0.10^{ns}	0.00^{ns}	335.68*	23.34*	10.88*
T/black	5	1.76^{ns}	0.67^{ns}	0.03*	262.92*	11.24^{ns}	4.46*
T/red	5	0.59^{ns}	1.20*	0.07*	264.08*	18.29*	9.70*
T/cranberry	4	3.25*	1.31*	0.01^{ns}	686.40*	11.09^{ns}	3.61*
Environment (E)	1	43.99*	7.30*	4.71*	4.74^{ns}	120.62^{ns}	41.00*
G x E	21	3.01*	1.12*	0.03*	177.62*	15.83*	2.03*
Error	84	0.60	0.14	0.00	8.38	2.39	0.20
Mean		12.44	5.53	1.16	77.44	23.57	9.08
CEV (%)		6.23	6.79	6.45	3.74	6.55	4.95
Selective accuracy		0.79	0.90	0.93	0.99	0.94	0.99

*Significant by the F-test, at 5% probability. ^{ns}Nonsignificant.

'IAC Netuno', 'BRS Pitanga', and 'BRS Executivo' of the black, red, and cranberry grain types, respectively, were part of the group with the highest Mg values. Despite this result, none of the evaluated common bean genotypes showed a high Mg concentration, which would be of ≥ 2.00 g kg^{-1} DM according to the classification of Ribeiro & Mezzomo (2020).

Fe was the micromineral present in the highest amount in all common bean genotypes, regardless of the grain type, in both seasons (Table 3), confirming the results obtained by Di Bella et al. (2016). However, in the dry season, the lowest and highest Fe concentrations of 59.67 and 95.67 mg kg^{-1} DM, respectively, were found for the red-grain genotype Amendoim Comprido and for the black bean cultivar BRS Campeiro. Similar Fe concentrations were found for common bean genotypes grown in Brazil (Pereira et al., 2011; Delfini et al., 2020; Ribeiro & Kläsener, 2020; Dias et al., 2021). In the present study, all common bean genotypes evaluated showed a high Fe concentration (≥ 60.40 mg kg^{-1} DM) considering the classes established by Tryphone & Nchimbi-Msolla (2010), except Amendoim comprido in the dry season. The use of foods biofortified with Fe is an alternative to prevent anemia, which is the most widely recognized clinical manifestation of Fe deficiency in the body (Dev & Babitt, 2017). Regardless of grain type, most common bean genotypes had a high Fe concentration

Table 2. Mean values obtained for concentrations of potassium (K), phosphorus (P), and magnesium (Mg) in grains of 22 common bean (*Phaseolus vulgaris*) genotypes evaluated in the dry and rainy seasons of 2019, in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil[(1)].

Genotype	K (g kg^{-1} dry matter)		P (g kg^{-1} dry matter)		Mg (g kg^{-1} dry matter)	
	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
			Carioca grain			
'BRSMG Madrepérola'	11.47b	12.87c	5.74a	5.08b	1.11a	1.24c
'IAC Imperador'	11.87a	12.20c	5.37b	5.27b	1.11a	1.28c
'IPR Siriri'	14.00a	12.07c	6.28a	4.75b	1.12a	1.37b
'Pérola'	12.13a	12.07c	6.18a	5.15b	1.06a	1.42b
'SCS205 Riqueza'	10.67b	12.60c	6.22a	4.83b	1.06a	1.36b
Mean	12.03	12.36	5.96	5.02	1.09	1.33
			Black grain			
'BRS Campeiro'	12.40a	13.33b	6.36a	5.00b	1.06a	1.39b
'BRS Esteio'	10.13b	13.13c	5.84a	5.07b	0.99b	1.33b
'Guapo Brilhante'	10.80b	13.73b	5.73a	4.72b	0.98b	1.30c
'IAC Netuno'	12.53a	13.40b	6.07a	5.60a	1.13a	1.53a
'IPR Tiziu'	11.60b	14.47a	6.25a	5.53a	1.02a	1.39b
'Macanudo'	12.27a	13.27b	5.62a	4.53b	0.96b	1.40b
Mean	11.62	13.56	5.98	5.08	1.03	1.39
			Red grain			
Amendoim comprido	12.00a	13.60b	6.26a	5.80a	0.81c	1.30c
'BRS Embaixador'	12.27a	12.27c	5.98a	4.94b	0.79c	1.08d
'BRS Pitanga'	11.33b	13.07c	6.07a	5.53a	0.96b	1.51a
Light Red Kidney	12.67a	13.07c	5.37b	4.50b	0.93b	1.26c
'Ouro vermelho'	13.33a	11.87c	6.37a	6.00a	1.05a	1.35b
Vermelho graúdo	11.33b	13.00c	6.13a	5.00b	0.80c	1.26c
Mean	12.16	12.81	6.03	5.30	0.89	1.29
			Cranberry grain			
'BRS Executivo'	11.60b	12.73c	6.08a	5.92a	0.79c	1.47a
'BRSMG Realce'	11.47b	13.67b	4.99b	5.92a	0.81c	1.36b
'BRS Radiante'	12.00a	15.00a	5.10b	5.90a	1.03a	1.28c
'Hooter'	12.93a	12.13c	3.73c	5.67a	0.80c	1.39b
'Iraí'	10.13b	12.80c	5.20b	5.84a	0.94b	1.38b
Mean	11.63	13.27	5.02	5.85	0.88	1.38

[(1)]Means followed by equal letters, in the columns, constitute a homogeneous group according to Scott-Knott's test, at 5% probability.

in the two seasons, indicating that their nutritional benefits should be further assessed.

Scott-Knott's test for Zn concentration in the dry season clustered the common bean genotypes into a single group, although a significant genotype effect was observed in this season. However, in the rainy season, four groups of common bean genotypes were formed. Only genotype Vermelho graúdo with red grains exhibited a high Zn concentration in the rainy season, i.e., ≥ 31.00 mg kg^{-1} DM according to the classes defined by Tryphone & Nchimbi-Msolla (2010). Common bean genotypes with a high Zn concentration have been previously selected in breeding programs (Silva et al., 2012; Dias et al., 2021; Ribeiro et al., 2021). The use of foods with a high Zn concentration is important for human health, since the deficiency in this nutrient reduces the body's resistance to infections (Zoroddu et al., 2019).

For Cu concentration, the greatest range of variation was observed in the rainy season – from 4.93 mg kg^{-1} for 'SCS205 Riqueza' to 12.20 mg kg^{-1} DM for 'BRS Embaixador'. These concentrations correspond to those described in previous studies on common bean genotypes (Ribeiro et al., 2014; McClean et al., 2017; Steckling et al., 2017; Delfini et al., 2020; Ribeiro & Kläsener, 2020). The highest Cu values were found for two genotypes with red grains: 'BRS Embaixador', in the dry and rainy seasons; and 'BRS Pitanga', in the

Table 3. Mean values obtained for concentrations of iron (Fe), zinc (Zn), and copper (Cu) in grains of 22 common bean (*Phaseolus vulgaris*) genotypes evaluated in the dry and rainy seasons of 2019, in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil[(1)].

Genotype	Fe (mg kg^{-1} dry matter)		Zn (mg kg^{-1} dry matter)		Cu (mg kg^{-1} dry matter)	
	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
			Carioca grain			
'BRSMG Madrepérola'	93.33a	84.34a	20.67a	22.40d	8.07c	10.40c
'IAC Imperador'	67.67d	75.84c	23.75a	27.53b	6.29d	8.43e
'IPR Siriri'	91.00a	75.74c	23.00a	21.20d	9.02b	10.53c
'Pérola'	90.00a	77.84c	21.94a	18.93c	8.25c	8.50e
'SCS205 Riqueza'	73.67c	72.04d	21.40a	24.83c	8.02c	4.93f
Mean	83.13	77.16	22.15	22.98	7.93	8.56
			Black grain			
'BRS Campeiro'	95.67a	79.97b	23.09a	21.73d	8.96b	9.67d
'BRS Esteio'	71.00c	73.60d	22.50a	26.60b	6.46d	8.43e
'Guapo Brilhante'	76.50c	72.17d	21.95a	24.13c	7.87c	10.37c
'IAC Netuno'	82.33b	69.07d	22.42a	21.30d	8.43c	10.53c
'IPR Tiziu'	63.00d	80.57b	21.81a	22.06d	9.26b	10.73c
'Macanudo'	63.00d	74.94c	23.86a	26.30b	8.47c	9.63d
Mean	75.25	75.05	22.60	23.69	8.24	9.89
			Red grain			
Amendoim comprido	59.67d	76.94c	21.93a	28.33b	7.85c	9.50d
'BRS Embaixador'	82.67b	79.84b	26.74a	24.93c	11.24a	12.20a
'BRS Pitanga'	84.67b	81.84b	22.89a	23.73c	10.50a	11.33b
Light Red Kidney	67.00d	73.24d	23.02a	24.70c	9.09b	9.10d
'Ouro vermelho'	83.67b	72.34d	23.48a	25.66b	8.01c	9.23d
Vermelho graúdo	65.33d	72.80d	23.29a	33.13a	9.01b	10.47c
Mean	73.83	76.16	23.56	26.75	9.29	10.31
			Cranberry grain			
'BRS Executivo'	64.00d	77.24c	22.51a	21.26d	8.07c	8.67e
'BRSMG Realce'	62.67d	73.30d	18.47a	26.46b	7.59c	9.30d
'BRS Radiante'	76.00c	88.94a	22.09a	23.06c	8.51c	9.43d
'Hooter'	92.67a	87.87a	23.36a	24.26c	9.41b	11.17b
'Iraí'	94.00a	87.40a	23.45a	27.13b	9.05b	9.40d
Mean	77.87	82.95	21.97	24.44	8.53	9.59

[(1)]Means followed by equal letters, in the columns, constitute a homogeneous group according to Scott-Knott's test, at 5% probability.

dry season. Since 'BRS Embaixador' stood out for Cu concentration in both seasons, it should be evaluated as a Cu source for food, aiming to minimize this nutrient's deficiency, which is related to symptoms as anemia and neutropenia (Wazir & Ghobrial, 2017).

When the multiplicative index analysis was performed with the data obtained in each growing season, heritability estimates ≥55.93% were observed for the mineral concentrations (Table 4). These values characterize intermediate to high heritability (Soltani et al., 2016), and are similar to the estimates obtained for the concentration of five minerals in landraces and commercial cultivars of common bean (Ribeiro et al., 2021). Intermediate to high magnitude heritability indicates a greater genetic variability in the concentrations of macro- and microminerals in common bean genotypes of the carioca, black, red, and cranberry types, which enables the selection of biofortified genotypes.

Total genetic gain estimates of 40.27 and 27.09% were observed in the dry and rainy seasons, respectively. Positive genetic gain estimates were also obtained in the selection of common bean genotypes with higher concentrations of microminerals (Dias et al, 2021) and minerals (Zanotti et al., 2020; Ribeiro et al., 2021). These results confirm that there is genetic

Table 4. Average of the original population (X_0), average of selected genotypes (Xs), heritability (h^2), genetic gain (GG), and percentage of genetic gain (GG%) with simultaneous selection by the multiplicative index for concentrations of potassium (K), phosphorus (P), magnesium (Mg), iron (Fe), zinc (Zn), and copper (Cu) in grains of 22 common bean (*Phaseolus vulgaris*) genotypes evaluated in the dry and rainy seasons of 2019, in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil.

Trait	X_0	X_S	h^2 (%)	GG	GG%	Selected genotype				
						'IPR Siriri'	'BRS Campeiro'	'BRS Embaixador'	'Ouro vermelho'	'IAC Netuno'
Dry season of 2019										
K (g kg^{-1})	11.86	12.91	74.27	0.78	6.55	14.00	12.40	12.27	13.33	12.53
P (g kg^{-1})	5.77	6.21	87.77	0.39	6.70	6.28	6.36	5.98	6.37	6.07
Mg (g kg^{-1})	0.97	1.03	83.55	0.05	5.28	1.12	1.06	0.79	1.05	1.13
Fe (mg kg^{-1})	77.25	87.07	97.29	9.55	12.36	91.00	95.67	82.67	83.67	82.33
Zn (mg kg^{-1})	22.62	23.74	55.93	0.63	2.79	23.00	23.09	26.74	23.48	22.42
Cu (mg kg^{-1})	8.52	9.13	91.53	0.56	6.59	9.02	8.96	11.24	8.01	8.43
Total gain					40.27					
Trait	X_0	X_S	h^2 (%)	GG	GG%	Selected genotype				
						'BRS Pitanga'	'Iraí'	'Hooter'	'BRS Radiante'	'IPR Tiziu'
Rainy season of 2019										
K (g kg^{-1})	13.01	13.49	73.57	0.35	2.70	13.07	12.80	12.13	15.00	14.47
P (g kg^{-1})	5.30	5.70	80.51	0.32	6.03	5.53	5.84	5.67	5.90	5.53
Mg (g kg^{-1})	1.35	1.39	85.90	0.04	2.81	1.51	1.38	1.39	1.28	1.39
Fe (mg kg^{-1})	77.63	85.32	95.06	7.31	9.42	81.84	87.40	87.87	88.94	80.57
Zn (mg kg^{-1})	24.53	24.05	93.87	-0.45	-1.84	23.73	27.13	24.26	23.06	22.06
Cu (mg kg^{-1})	9.63	10.41	98.58	0.77	7.97	11.33	9.40	11.17	9.43	10.73
Total gain					27.09					
Trait	X_0	X_S	h^2 (%)	GG	GG%	Selected genotype				
						Amendoim comprido	Light Red Kidney	'BRS Executivo'	'IPR Siriri'	'Hooter'
Combined analysis (mean of the two seasons)										
K (g kg^{-1})	31.84	12.00	62.60	-12.42	-39.01	14.40	11.60	11.60	11.20	11.20
P (g kg^{-1})	9.93	6.11	81.40	-3.11	-31.29	6.24	6.68	5.93	5.43	6.29
Mg (g kg^{-1})	3.73	1.12	87.38	-2.28	-61.23	1.29	1.14	0.94	1.14	1.07
Fe (mg kg^{-1})	30.64	87.40	97.69	55.45	181.00	89.00	92.00	88.00	94.00	74.00
Zn (mg kg^{-1})	10.19	21.75	87.97	10.17	99.79	25.17	19.55	23.57	19.26	21.21
Cu (mg kg^{-1})	3.43	8.16	97.48	4.61	134.33	8.70	7.99	8.01	8.46	7.64
Total gain					283.59					

variability in the mineral concentrations in common bean genotypes of different grain types that can be exploited by breeding programs in the development of biofortified cultivars.

The five superior common bean genotypes for mineral concentrations selected in the dry season differed from those in the rainy season. This is explained by the fact that there was a significant effect of the genotype × environment interaction on the concentration of all evaluated minerals (Table 1). When this happens, the identification of superior genotypes will vary with the growing environment (Tables 2, 3, and 4), making the selection process difficult. Therefore, it is important to consider the environmental variability between growing seasons in a same experimental site when performing combined selection for various minerals in common bean genotypes.

The multiplicative index analysis using the average data obtained in the two growing seasons (combined analysis) revealed high heritability estimates of ≥ 62.60% and a higher total genetic gain estimate of 283.59% (Table 4). Therefore, when the environmental variability between growing seasons was considered, it was possible to analyze a greater range of genetic variability, which results in a greater gain from the selection of common bean genotypes with high macro- and micromineral concentrations. In this case, a greater efficiency is expected when biofortified common bean is selected based on data from both growing seasons.

The multiplicative index, applied to data from the two seasons, allowed the selection of common bean genotypes of the following grain types: red (Amendoim comprido and Light Red Kidney), cranberry ('BRS Executivo' and 'Hooter'), and carioca ('IPR Siriri'). These five common bean genotypes have high concentrations of P (≥ 5.00 g kg^{-1} DM) and Fe (≥ 60.40 mg kg^{-1} DM), whereas Amendoim comprido also has a high K concentration (≥ 12.00 g kg^{-1} DM). Considering that deficiencies in these minerals cause several health problems, such as those reported by Dev & Babitt (2017), McDonough & Youn (2017) and Serna & Bergwitz (2020), the inclusion of common bean genotypes with higher concentrations of P, Fe, and K into diets needs to be evaluated.

Genotypes Amendoim comprido, Light Red Kidney, 'BRS Executivo', 'Hooter', and 'IPR Siriri' stood out for their high concentration of two or three minerals and, therefore, are promising for the nutritional enrichment of diets and for use in breeding programs with emphasis on the genetic biofortification of common bean. However, the bioavailability of those minerals in common bean genotypes must be assessed to validate grain health benefits.

Conclusions

1. There is genetic variability in the concentrations of macro- and micromineral in common bean (*Phaseolus vulgaris*) genotypes evaluated in the dry and rainy seasons.
2. High heritability estimates and a greater total genetic gain are detected in combined experiments.
3. The multiplicative index applied to combined experiments allows the selection of superior common bean genotypes of the following grain types: red (Amendoim comprido and Light Red Kidney), cranberry ('BRS Executivo' and 'Hooter'), and carioca ('IPR Siriri'), all with high P and Fe concentrations, and Amendoim comprido also with a high K concentration.
4. Potassium is the macromineral and iron is the micromineral found in the highest amount in the common bean genotypes, regardless of the grain type, in both growing seasons.

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