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Genetic gain for technological traits in new cultivars developed by the Southern Brazilian common-bean network

Ganho genético para caracteres tecnológicos de novas cultivares desenvolvidas pela rede sul brasileira de feijão

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ABSTRACT

Estimating the genetic gain obtained for technological quality traits over the years makes it possible to analyze whether the changes made meet consumer preferences, which represents an important innovation for common-bean breeding programs. The objectives of this study were to obtain genetic gain estimates for technological grain quality traits of common bean lines and investigate whether the modifications made were favorable in the context of sustainability and food and nutritional security for the coming generations. Twenty-four experiments were conducted between the years 2010 and 2022 and a total of 75 common bean lines were evaluated. Genetic gains of technological grain quality traits were determined by the Vencovsky's (1988) method adapted for biennia. There was a significant effect of genotype for most traits evaluated, which shows the existence of genetic variability. Mass of 100 grains and water absorption had a negative genetic gain of -2.91% and -0.55% per year, respectively, indicating a reduction in these traits. Genetic gain was zero for L* value (lightness) and cooking time, denoting a plateau for these traits. Most of the common bean lines exhibit adequate L* values for carioca (L* ≥ 53) and black (L* ≤ 22) bean grains; a mass of 100 grains from 20 to 25 g; and fast cooking (≤ 25 min). The new common bean cultivars released for cultivation in the southern region of Brazil have high technological grain quality, being favorable in a context of sustainability and food and nutritional security for the coming generations.

Index terms: *Phaseolus vulgaris* L.; grain color; grain size; cooking time; selection cycles.

RESUMO

Estimativas de ganho genético para caracteres da qualidade tecnológica obtidas ao longo dos anos permitem analisar se as mudanças realizadas atendem a preferência dos consumidores, o que representa uma importante inovação para os programas de melhoramento de feijão. Os objetivos deste trabalho foram obter estimativas de ganho genético para caracteres da qualidade tecnológica de grãos em linhagens de feijão e analisar se as modificações efetuadas foram favoráveis em um contexto de sustentabilidade e de segurança alimentar e nutricional das próximas gerações. Um total de 24 experimentos foram conduzidos entre os anos de 2010 a 2022, avaliando 75 linhagens de feijão. O ganho genético dos caracteres da qualidade tecnológica foi determinado pelo método de Vencovsky (1988), adaptado para biênios. Efeito significativo para genótipo foi observado para a maioria dos caracteres, evidenciando que há variabilidade genética. Massa de 100 grãos e absorção de água apresentaram ganho genético negativo de -2,91% e de -0,55% por ano, respectivamente, indicando redução nestes caracteres. Ganho genético nulo foi constatado para o valor de L* (luminosidade) e para tempo de cozimento, evidenciando um platô nesses caracteres. A maioria das linhagens de feijão apresenta valores de L* adequados para grãos carioca (L* ≥ 53) e preto (L* ≤ 22), massa de 100 grãos de 20 a 25 g e cozimento rápido (≤ 25 min). As novas cultivares de feijão lançadas para o cultivo na região Sul do Brasil têm alta qualidade tecnológica, sendo favoráveis em um contexto de sustentabilidade e de segurança alimentar e nutricional das próximas gerações.

Termos para indexação: *Phaseolus vulgaris* L.; coloração dos grãos; tamanho dos grãos; tempo de cozimento; ciclos de seleção.

INTRODUCTION

The consumption of common bean (*Phaseolus vulgaris* L.) is part of the eating habits of people from different countries. The existing diverse sizes, colors, and shapes of common bean grains that can be included in the diet meet the preferences of the most varied consumer profiles. Furthermore, there are many ways of preparing this healthy food, which has several health-protective effects (Chávez-Mendoza; Sánchez, 2017).

One way to encourage the consumption of common bean is to develop new cultivars with higher technological grain quality. The technological quality of common bean grains has been especially evaluated by their color, size, and cooking time (Arns et al., 2018; Ribeiro et al., 2019, 2021, 2023; Kläsener; Ribeiro; Argenta, 2022). The grain types of *Phaseolus vulgaris* most produced in Brazil originate from the Mesoamerican gene pool, namely, carioca (beige seed coat with brown streaks), black, red, and pink, whose grain size ranges from small (< 25 g 100 grains^{-1}) to medium (25 to 40 g 100 grains^{-1}) according to the classes described by Hegay et al. (2014). In some regions of the country, grains from the Andean gene pool are also cultivated, especially the cranberry (cream seed coat with red streaks), red, and white types, which are characterized by their medium-to-large size (> 40 g 100 grains^{-1}).

However, 85% of common bean consumption in Brazil is restricted to two types of beans: carioca and black (Pereira et al., 2019). As a result, common-bean breeding programs have dedicated greater effort to the development of new carioca and black bean cultivars with technological grain quality that meet consumer preferences. To this end, the following grain standards have been used as a reference in the selection of superior common bean lines: high lightness for carioca beans, defined as an L* value ≥ 55 by Arns et al. (2018); low lightness for black beans, stipulated as an L* value ≤ 22 by Ribeiro, Possebom and Storck (2003); mass of 100 grains from 25 to 30 g (Carbonell et al., 2010); and fast cooking (≤ 25 min) (Santos; Ribeiro; Maziero, 2016) for carioca and black beans.

Common-bean breeding programs in Brazil have developed many lines with high technological grain quality in the 2010s (Santos; Ribeiro; Maziero, 2016; Arns et al., 2018; Kläsener; Ribeiro; Argenta, 2022; Ribeiro et al., 2023; Ribeiro; Maziero, 2023). As improvement of technological grain quality traits is relatively recent in common bean, no information was found in the literature on whether genetic gain was achieved for the these traits over several selection cycles. These results would make it possible to assess whether the strategies used by common-bean breeding programs in Brazil were efficient in improving grain color, increasing grain size, and reducing the cooking time of common bean lines. In addition, it would serve as a basis for identifying and recommending changes to be incorporated in the new common bean cultivars in order to allow a continuous and gradual improvement of technological grain quality traits.

Several methodologies have been used to estimate the genetic gain of important traits for selection in breeding programs. The Vencovsky's (1988) method (Cruz; Regazzi; Carneiro, 2012) has been shown to be efficient in obtaining genetic gain estimates for grain yield in wheat (Follmmann et al., 2017; Woyann et al., 2019) and rice (Silva Júnior et al., 2021) breeding programs and for different agronomic traits evaluated in common bean breeding (Ribeiro; Possebom; Storck, 2003; Ribeiro et al., 2008). For technological grain quality traits of common bean, genetic gain estimates are restricted to a few traits evaluated in a short period (Ribeiro; Possebom; Storck, 2003). Mass of 100 grains has been the most analyzed technological trait in common-bean breeding programs, and genetic gain has been estimated by different methodologies (Singh et al., 2007; Ribeiro et al., 2008; Faria et al., 2013, 2014; Bekele et al., 2019; Kefelegn; Mekibib; Dessalegn, 2020; Mukayiranga et al., 2022). However, no previous studies were found that determined genetic gain for traits of grain color, water absorption, or cooking time using databases generated over years in common-bean breeding programs.

Therefore, the present study was undertaken to obtain genetic gain estimates of technological grain quality traits of common bean lines and investigate whether the changes made to these traits were favorable in the context of sustainability and food and nutritional security for the coming generations.

MATERIAL AND METHODS

Experimental conduct and data collection

The Value for Cultivation and Use (VCU) experiments of the Southern Brazilian Common-Bean Network were conducted following the rules for registering new cultivars in Brazil (Ministério da Agricultura, Pecuária e Abastecimento - Mapa, 2006). A randomized block design with three replicates was employed. Each experimental plot consisted of four 4-m rows, with 0.5 m spacing between rows and a total area of 8 m^2. Only the two central rows constituted the usable area of the plots (4 m^2). The sowing density adopted was 15 seeds per linear meter.

In each experiment, the number of common bean genotypes (lines and cultivars) evaluated ranged from 11 to 18, in a total of 75 common bean genotypes. These genotypes were developed between 2010 and 2022 by eight public research institutions in Brazil: Embrapa Rice and Beans, Embrapa Temperate Climate, Agronomic Institute of Campinas, Institute of Rural Development of Paraná, Agricultural Research and Rural Extension Corporation of Santa Catarina, State University of Maringá, Federal University of Santa Maria (UFSM), and Department of Diagnosis and Agricultural Research of the Secretariat of Agriculture, Livestock, and Rural Development of the State of Rio Grande do Sul (RS). In this period, common bean genotypes of the Mesoamerican and Andean gene pools with the following grain types were analyzed: black, carioca, cranberry, red, and pink. The common bean genotypes evaluated characterize a representative sample of the genetic diversity generated by public common-bean breeding programs in Brazil.

The composition of the VCU experiments is defined by the Breeding Subcommittee at the Southern Brazilian Common-Bean Meeting, which is held in July in even-numbered years. Each institution may include up to two new lines in each selection cycle (biennium). In each biennium, crops are grown in three seasons (rainy, dry, and winter) and in two consecutive years (even and odd). The lines evaluated in these experiments will not change within the biennium.

The experiments conducted by the Southern Brazilian Common-Bean Network are established in different municipalities in the states of Rio Grande do Sul, Santa Catarina, Paraná, São Paulo, and Goiás, at the recommended sowing times for each region, totaling approximately 100 experiments per biennium. In each biennium, lines released as new cultivars, unreleased lines, and four cultivars registered for cultivation in southern Brazil (controls) were evaluated. Therefore, one or more released lines may have been also analyzed as a cultivar in these experiments.

Genetic gain estimates were obtained using only databases generated at the Federal University of Santa Maria, located in Santa Maria, RS, Brazil. This is because the tecnological quality traits are not evaluated in the routine all common-bean breeding programs. Additionally, the quantitative assessment of grain color (L* value) was only carried out in Santa Maria. Grain color is an important technological trait that can be decisive for the acceptance of a common bean cultivar by the consumer (Ribeiro et al., 2019). However, the quantitative determination of grain color is not required for the registration of common bean cultivars in Brazil (Mapa, 2006).

A total of 24 common-bean VCU experiments were sown in Santa Maria between the years 2010 and 2022 in the two recommended seasons for cultivation: rainy (September or October) and dry (January or February). The climate of the region is humid subtropical, without a clearly defined dry season, and the experimental area is located at the following geographic coordinates: 29º42' S latitude, 53º49'W longitude, and 95 m above sea level.

The soil is a typic alitic Argisol, Hapludalf (Santos et al., 2018), which was prepared by the conventional tillage system, with one plowing and two harrowing operations. Limestone and fertilizer applications were based on the interpretation of soil chemical analysis for each experiment. Seed treatment with insecticide and fungicide and insect control were carried out using chemicals registered for the crop and with variable active ingredients over the years. In compliance with the rules of Mapa (2006), fungicides were not applied to control shoot diseases. Irrigation was only performed when necessary to establish the initial plant population and when there was an imminent risk of losing the experiment due to lack of rainfall during the reproductive period of the crop.

Determination of technological grain quality traits

The crop was harvested at the maturity stage (R9), that is, when the pods were dry and the grains were the typical color of each genotype. Harvesting and grain processing were carried out manually to avoid mechanical damage. The grains were dried naturally in the sun and, if necessary, in an oven, up to 13% moisture. Then, beans were stored in a cold chamber (temperature of 5 ºC and relative moisture of 75%) for approximately one month before the beginning of the evaluations of technological traits.

Grain color was determined using a portable colorimeter (CR 410, Konica Minolta, Osaka, Japão) operating in the CIELAB system. On this scale, the value of L* characterized grain lightness, which could range from 0 (black) to 100 (white). A sample of grains was randomly collected in each replicate and distributed inside a petri dish 6 cm in diameter and 1.5 cm in height, filling the entire surface. The petri dish was placed on white paper to prevent the absorption of possible colors from the environment. Grain color were taken in three readings of each replicate (Ribeiro et al., 2021). Mass of 100 grains (g) was calculated as the average weight of three samples of 100 grains collected at random in each replicate.

Water absorption and cooking time were quantified in a random sample of 25 grains. The grains remained in contact with 50 mL of distilled water for 8 h, at room temperature (20 ± 2 ºC). The water was removed and water absorption was calculated by the following expression: [(grain weight after soaking – grain weight before soaking)/grain weight before soaking] × 100. Cooking time was evaluated in a 25-plunger Mattson cooker in a method similar to that described by Ribeiro et al. (2021).

Statistical analyses

Analysis of variance was performed for each of the experiments. For the water absorption data, $\sqrt{x+0.5}$ transformation was applied, in which corresponds to the trait value, and cooking time was converted into s.

Genetic gain was determined by the Vencovsky's (1988) method, also known as the generalized least squares method (Cruz; Regazzi; Carneiro, 2012), adapted for biennia. Each biennium begins with rainy season cultivation in the even year and ends with dry season cultivation in the odd year. Genetic gain estimates were obtained by identifying genotypes common to two successive biennia and estimating the mean $\left(\overline{Y}_{ci}\right)$ for each biennium. Data were collected in *n* biennia, and genetic gain (G_{ak}) per biennium, relative to the previous biennium, was determined by the following Equation 1:

$$G_{ak} = \overline{Y}_i - \overline{Y}_j - \left(\overline{Y}_{ci} - \overline{Y}_{cj}\right) \quad (1)$$

in which:
G_{ak} = genetic gain between biennia i and j;
$\overline{Y}_i$ = overall mean of genotypes in biennium i;
$\overline{Y}_j$ = overall mean of genotypes in biennium j, since j = i + 1;
$\overline{Y}_{ci}$ = overall mean of common genotypes in biennium i; and
$\overline{Y}_{cj}$ = overall mean of common genotypes in biennium j.

Total genetic gain was estimated by Equation 2:

$$Ga = \sum_{k=1}^{n-1} Ga_k \quad (2)$$

The mean annual genetic gain was obtained by Equation 3:

$$Ga = \sum_{n-1}^{k=1} Ga_k \quad (3)$$

RESULTS AND DISCUSSION

Individual analysis of variance

Of the 24 VCU experiments established, lost plots were not detected only in 16 experiments. This is because high precipitation intensity was recorded in eight experiments, especially in the weeks prior to the harvest, which contributed to the reduction in quantity and quality of the grains produced. As a consequence, data from three experiments conducted in the rainy season crop (2011, 2013, and 2018) and five experiments in the dry season crop (2012, 2014, 2016, 2020, and 2022) were not included in the genetic gain analyses. In a climate change scenario, experiment losses caused by adverse environmental factors, such as high temperature, excessive precipitation, among others, will be more frequent, generating unbalanced data and this needs to be evaluated when obtaining estimates of genetic gain.

All traits evaluated in the 16 experiments showed a significant genotype effect, except for water absorption determined in the 2010, 2014, and 2015 rainy season crops and the 2018 dry season crop (Table 1). These results evidence that the lines developed by the Southern Brazilian Common-Bean Network have genetic variability for technological grain quality traits. Previous studies reported great genetic diversity for technological grain quality traits analyzed in lines (Arns et al., 2018; Ribeiro et al., 2023), cultivars (Kläsener; Ribeiro; Argenta, 2022), and landraces (Ribeiro et al., 2021) of common bean. Therefore, greater genetic variability for technological grain quality traits facilitates the selection of common bean lines with color, grain size, and cooking time that meet the needs and preferences of consumers.

The different traits showed coefficients of experimental variation ≤ 19.56%. Conversely, all traits that exhibited significant differences for genotype had selective accuracy ≥ 0.76, characterizing high experimental precision according to Resende and Alves (2020). The coefficient of experimental variation and selective accuracy values observed in the present study are comparable, in magnitude, to those of technological grain quality traits determined in common bean genotypes (Arns et al., 2018; Dias et al., 2021; Kläsener; Ribeiro; Argenta, 2022; Ribeiro et al., 2021, 2023). Therefore, the technological grain quality traits were evaluated with high experimental precision, which allows greater reliability in obtaining genetic gain estimates for these traits.

Genetic gain by the Vencovsky's (1988) method (Cruz; Regazzi; Carneiro, 2012)

The VCU experiments of the Southern Brazilian Common-Bean Network are characterized by a high rate of substitution of the lines evaluated in each selection cycle (biennium), keeping only one to four control cultivars between two consecutive biennia (Table 2). The Vencovsky's (1988) method (Cruz; Regazzi; Carneiro, 2012) considers the superiority of the lines that are evaluated in a selection cycle relative to the previous cycle to estimate the genetic gain of different traits. This method was appropriate for obtaining consistent genetic gain estimates using unbalanced data from few environments (Ribeiro; Possebom; Storck, 2003; Ribeiro et al., 2008; Follmmann et al., 2017; Silva Júnior et al., 2021; Woyann et al., 2019).

Environmental gain estimates were higher than genetic gain estimates for all analyzed traits (Table 3). In previous experiments conducted by the common-bean breeding program (Ribeiro et al., 2008) and by a rice breeding program (Silva Júnior et al., 2021), the generalized least squares method also provided high environmental gain estimates. The strategy of keeping a greater number of common treatments between selection cycles provides greater safety in estimating environmental variance (Cruz; Regazzi; Carneiro, 2012). However, keeping a large number of common lines and/or cultivars in experiments conducted in different biennia implies greater costs, area, and labor to conduct and evaluate the VCU experiments. Because the Southern Brazilian Common-Bean Network is constituted only of public research institutions, which would mean that there would be a limited budget for conducting the VCU experiments, evaluating a large number of common treatments is unfeasible.

In the present study, climatic factors, particularly temperature stress and high precipitation; and biotic factors, e.g. the occurrence of diseases and pests, contributed to the high environmental influence. Considering that the VCU experiments were conducted over 12 years and in the two recommended growing seasons (rainy and dry), the observed environmental variability is representative of the growing conditions for common bean in the region.

Table 1: Analysis of variance containing the degrees of freedom (DF), mean squares, coefficient of experimental variation (CEV), and selective accuracy (SA) for the following traits: L* value (L*), mass of 100 grains (M100G), water absorption (ABS), and cooking time (time) in 16 common bean experiments carried out between 2010 and 2021.

Sources of variation	DF	Mean square				DF	Mean square			
		L*	M100G (g)	ABS (%)	TIME (min:s)		L*	M100G (g)	ABS (%)	TIME (s)
	2010 rainy					2011 dry				
Block	2	1.73	3.27	0.44	30293.78	2	0.27	2.82	0.11	26308.89
Genotype	13	831.82*	32.70*	1.02ns	53033.53*	15	972.75*	61.74*	3.02*	43076.40*
Error	26	0.46	1.46	0.90	9240.52	30	0.47	2.30	0.28	12183.34
Mean		32.01	21.56	86.52	17:10		34.98	23.59	82.79	16:46
CEV (%)		2.13	5.61	10.17	9.33		1.95	6.43	5.79	10.98
SA		1.00	0.98	0.34	0.91		1.00	0.98	0.95	0.85
	2012 rainy					2013 dry				
Block	2	15.97	2.33	2.64	25266.89	2	0.41	4.28	0.01	172775.14
Genotype	13	948.32*	12.58*	3.86*	34475.57*	13	947.99*	63.01*	5.91*	102753.38*
Error	26	2.22	5.20	0.34	9472.19	26	1.37	2.71	0.10	30056.86
Mean		40.35	19.47	83.32	18:02		40.58	18.83	73.12	23:50
CEV (%)		3.69	11.71	6.36	9.00		2.88	8.74	3.75	12.12
SA		1.00	0.77	0.95	0.85		1.00	0.98	0.99	0.84
	2014 rainy					2015 dry				
Block	2	2.09	0.59	0.58	8714.38	2	0.50	1.07	0.65	4531.45
Genotype	13	696.08*	5.17*	0.59ns	29762.45*	13	696.06*	18.50*	0.79*	19849.89*
Error	26	0.75	0.84	0.28	5188.12	26	0.62	2.45	0.16	6484.55
Mean		42.40	22.48	92.20	15:42		42.53	21.84	78.94	13:42
CEV (%)		2.04	4.07	5.53	7.64		1.85	7.17	4.47	9.80
SA		1.00	0.91	0.72	0.91		1.00	0.93	0.89	0.82

Continue...

Table 1: Continuation.

			2015 rainy					2016 rainy		
Block	2	2.07	2.86	0.15	21145.66	2	0.29	35.61	0.02	20259.78
Genotype	13	680.54*	19.12*	0.35ns	48617.68*	16	782.71*	25.97*	2.24*	32178.38*
Error	26	1.76	4.32	0.40	11699.21	32	1.67	9.08	0.08	6350.16
Mean		41.13	22.05	100.53	21:05		38.35	23.82	89.98	21:56
CEV (%)		3.23	9.43	6.31	8.55		3.37	12.65	3.00	6.06
SA		1.00	0.88	0.00	0.87		1.00	0.81	0.98	0.89
			2017 dry					2017 rainy		
Block	2	1.22	2.21	0.35	23800.37	2	12.47	3.98	0.34	378542.82
Genotype	16	964.70*	57.17*	5.15*	59278.75*	16	995.76*	18.45*	1.36*	42733.19*
Error	32	0.79	2.30	0.37	6605.68	32	2.85	3.84	0.35	18058.59
Mean		39.72	23.49	89.66	14:24		40.17	25.18	100.34	18:22
CEV (%)		2.24	6.46	6.45	9.41		4.21	7.79	5.92	12.19
SA		1.00	0.98	0.96	0.94		1.00	0.89	0.86	0.76
			2018 dry					2019 dry		
Block	2	1.43	1.53	0.02	5234.37	2	3.36	4.20	0.01	82903.42
Genotype	16	1035.74*	20.55*	0.20ns	18942.71*	17	1016.82*	58.10*	8.88*	171014.85*
Error	32	1.20	2.24	0.10	3402.12	34	1.64	5.08	0.60	28757.52
Mean		40.10	30.69	76.15	12:31		41.05	26.07	86.37	15:13
CEV (%)		2.73	4.88	3.69	7.77		3.12	8.65	8.30	18.58
SA		1.00	0.94	0.68	0.90		1.00	0.95	0.96	0.91
			2019 rainy					2020 rainy		
Block	2	2.03	5.61	0.17	15174.45	2	2.84	0.56	0.18	9684.11
Genotype	16	776.50*	15.53*	0.92*	31426.09*	11	791.16*	21.35*	0.22*	68855.30*
Error	32	1.53	2.00	0.23	11430.55	22	2.44	2.09	0.05	7318.87
Mean		39.94	21.64	96.39	16:59		35.55	24.46	98.82	18:13
CEV (%)		3.10	6.54	4.87	10.50		4.40	5.91	2.16	7.83
SA		1.00	0.93	0.86	0.80		1.00	0.95	0.89	0.94
			2021 dry					2021 rainy		
Block	2	0.55	0.90	0.39	235.03	2	0.04	2.10	0.04	11928.78
Genotype	10	1184.96*	5.98*	2.86*	210030.62*	11	846.21*	14.17*	0.16*	38837.17*
Error	20	0.20	0.55	0.35	33763.66	22	0.60	2.61	0.03	9351.17
Mean		35.63	24.27	74.17	15:39		35.71	20.28	94.21	16:53
CEV (%)		1.26	3.06	6.83	19.56		2.17	7.97	1.66	9.54
SA		1.00	0.95	0.94	0.92		1.00	0.90	0.91	0.87

*Significant by F test at 0.05 probability; ns: non-significant.

The genetic gain obtained for the L* value was 0.05 biennium^{-1}, representing an increase of 0.13% per year (Table 3). Similarly, a low genetic gain estimate for the L* value was described for carioca and black bean lines evaluated in Santa Maria-RS between the years 1998 and 2001, using the generalized least squares method (Ribeiro; Possebom; Storck, 2003). These values indicate a plateau for grain L* value (lightness) in the new carioca and black bean cultivars released for cultivation in the southern region of Brazil. This can be explained by the fact that common

Table 2: Identification of the experiments that composed each of the six evaluated biennia; number of new lines relative to the previous biennium (new), kept lines for evaluation in the subsequent biennium (kept), excluded lines from the evaluation of the subsequent biennium (excluded), and evaluated lines in the biennium (evaluated); and number of lines with black, carioca, and other grain types evaluated by the Southern Brazilian Common-Bean Network between 2010 and 2022.

Biennia	Identification of the experiments	New	Kept	Excluded	Evaluated	Grain type		
						black	carioca	other
1	2010 rainy, 2011 dry, 2011 rainy, and 2012 dry	0	4	12	16	9	5	2
2	2012 rainy, 2013 dry, 2013 rainy, and 2014 dry	10	4	10	14	6	8	0
3	2014 rainy, 2015 dry, 2015 rainy, and 2016 dry	10	4	10	14	5	9	0
4	2016 rainy, 2017 dry, 2017 rainy, and 2018 dry	13	1	16	17	8	9	0
5	2018 rainy, 2019 dry, 2019 rainy, and 2020 dry	17	3	15	18	8	7	3
6	2020 rainy, 2021 dry, 2021 rainy, and 2022 dry	9	12	0	12	7	5	0

Table 3: Balance of the genetic and environmental gain – mean and in parentheses percentage, obtained by breeding program of the Southern Brazilian Common-Bean Network between 2010 and 2022 for the traits L* value, mass of 100 grains, water absorption, and cooking time.

Trait	Gain		
	Genetic	Environmental	Total
L* value	0.05 (21.67[1])	0.18 (78.33[2])	0.24 (100)
Mass of 100 grains (g)	-0.66 (-80.23)	1.48 (180.23)	0.82 (100)
Water absorption (%)	-0.48 (143.01)	-0.50 (-43.01)	-0.98 (100)
Cooking time (min:s)	-00:03 (18.25)	-00:12 (81.75)	00:14 (100)

[1]Genetic gain (%): genetic gain/total gain*100.
[2]Environmental gain (%): environmental gain/total gain*100.

parents were used in several controlled crosses carried out to develop the new carioca and black bean cultivars, resulting in a narrow genetic base (Veloso et al., 2015). This is especially true for the carioca bean cultivars, which have less genetic diversity (Almeida et al., 2020). The hypothesis is that the selection pressure adopted in breeding programs for technological grain quality traits, such as resistance to browning, larger grain size, and reduced cooking time, prioritized in Brazil from 1997 onwards (Chiorato et al., 2010), contributed to the stabilization of genetic gain for the color of carioca and black bean grains.

In all biennia, the mean L* values of the new common bean lines was higher than the mean of the lines kept (control cultivars) in the experiments, except for biennium 4 (Table 4). These results show that the new carioca bean cultivars had grains with the same or greater lightness (higher L* value) than those of the carioca bean control cultivars. The development of carioca bean cultivars with grains with an L* value ≥ 53 meets the demand of consumers who prefer very light grains (Ribeiro et al., 2019). Additionally, black bean cultivars with grain lightness equal to or lower (lower L* value) than that of black bean control cultivars were obtained. For black bean cultivars, the color standard used in the selection of superior lines is an L* value ≤ 22, as it characterizes the absence of purplish grains (Ribeiro; Possebom; Storck, 2003). Most of the lines obtained by the research institutions that constitute the Southern Brazilian Common-Bean Network between the years 2010 and 2022 have carioca and black beans with a grain color that meets the market demand, increasing the probability of acceptance of the new cultivars by consumers.

Mass of 100 grains showed a negative genetic gain of -0.66 g biennium^{-1}, which corresponds to a reduction of -2.91% per year (Table 3). However, for Great Northern and pink common bean lines grown in the United States were obtained positive and high magnitude genetic gain estimates for mass of 100 grains, whereas for pinto and red common bean lines were observed low magnitude estimates, using mixed models (Singh et al., 2007).

Positive genetic gain for mass of 100 grains has also been described for black bean lines (Faria et al., 2014) and for common bean cultivars of various grain types and sizes grown in Ethiopia (Bekele et al., 2019; Kefelegn; Mekibib; Dessalegn, 2020), by the regression analysis method. Nonetheless, non-significant genetic gain estimates were found for mass of 100 grains in carioca bean lines (Faria et al., 2013) and for common bean cultivars of different grain types and with upright plant architecture grown in Uganda (Mukayiranga et al., 2022), using the regression analysis method. These results show that the genetic gain for mass of 100 grains in common bean varies according to the grain type, number of lines, evaluation period, environment in which the experiments were conducted, and estimation method. In the present study, the genetic gain estimates obtained for mass of 100 grains reveal that the new common bean cultivars released between the years 2010 and 2022 in the southern region of Brazil have smaller grains.

The decrease in mass of 100 grains can be attributed to the fact that, from biennium 4, which started in the cultivation of the 2016 rainy crop, the average mass of 100 grains of the new lines included in the VCU experiments was lower than that of the control cultivars (Table 4). Therefore, in recent years, many common bean lines with small grains (< 25 g 100 grains^{-1}) have been evaluated in the VCU experiments. For the grain types most widely produced in Brazil, carioca and black, the recommended standard mass of 100 grains is from 25 to 30 g, that is, medium-sized grains (Carbonell et al., 2010).

Table 4: Mean obtained for new lines relative to the previous biennium (new), kept lines for evaluation in the subsequent biennium (kept), excluded lines from the evaluation of the subsequent biennium (excluded), and evaluated lines in the biennium (evaluated) for the traits of L* value, mass of 100 grains, water absorption, and cooking time in the six evaluated biennia.

Biennia	1	2	3	4	5	6
			L* value			
New	-1.00	41.58	43.79	40.16	39.96	36.95
Kept	37.48	37.67	37.60	54.37	33.77	36.11
Excluded	32.75	41.58	43.79	38.66	42.32	-1.00
Evaluated	33.93	40.47	42.02	39.58	40.89	36.11
			Mass of 100 grains (g)			
New	-1.00	19.88	22.43	26.00	24.22	22.50
Kept	20.06	17.31	21.36	29.04	24.35	22.93
Excluded	23.69	19.88	22.43	25.60	24.28	-1.00
Evaluated	22.78	19.15	22.12	25.80	24.29	22.93
			Water absorption (%)			
New	-1.00	84.62	91.07	91.59	91.16	89.86
Kept	76.59	63.10	88.52	95.15	77.53	89.39
Excluded	87.94	84.62	91.07	88.44	93.78	-1.00
Evaluated	85.03	78.15	90.33	88.82	90.97	89.39
			Cooking time (min:s)			
New	-1.00	20:29	16:43	16:45	16:05	16:57
Kept	17:00	22:02	17:06	17:44	15:05	16:56
Excluded	16:53	20:29	16:43	16:45	16:09	-1.00
Evaluated	16:55	20:56	16:50	16:48	15:58	16:56

This is because medium-sized grains are more accepted by common bean consumers in Brazil (Ribeiro et al., 2019). In this way, the selection strategies used by the breeding programs of the Southern Brazilian Common-Bean Network must be modified so that new carioca and black bean cultivars with medium-sized grains are developed. An option to increase grain size in common bean that needs to be assessed by breeding programs is the introgression of genes from Andean bean pool.

Water absorption exhibited a negative genetic gain of -0.48% biennium^{-1}, that is, a decrease of -0.55% per year (Table 3). No genetic gain estimates for water absorption using databases obtained over several selection cycles in common-bean breeding programs were found in the literature. However, water absorption displayed zero and positive genetic gain for carioca and black bean lines, respectively, when determined by the multiplicative index, based on data from experiments conducted over two years and in two growing seasons (Ribeiro; Maziero, 2023). The conflicting results observed can be explained by the evaluation period considered to obtain the genetic gain estimates for water absorption. Genetic gain estimates based over a longer experimental period are more consistent and allow a better understanding of the changes made to the technological grain quality traits of common bean over several selection cycles.

The negative genetic gain obtained for water absorption demonstrates that there was a reduction in water absorption capacity in the period during which the grains remained soaked before cooking. In common bean, water absorption and cooking time are negatively correlated, which allows selection for higher water absorption percentage to be efficient for the indirect selection of lines with a shorter cooking time (Kläsener; Ribeiro; Argenta, 2022). The results obtained in the present study indicate that the breeding programs that constituted the Southern Brazilian Common-Bean Network between the years 2010 and 2022 did not prioritize an increase in water absorption.

Cooking time had a genetic gain of -3 s biennium^{-1}, which corresponds to a percentage of -0.25% per year (Table 3), considered zero. No studies were found in the literature investigating genetic gains for cooking time in common bean lines as estimated from experiments conducted over one or more decades by the breeding program. However, between the years 2016 and 2018, zero genetic gain was observed for cooking time in carioca and black bean lines developed for cultivation in the southern region of Brazil, using the multiplicative index (Ribeiro; Maziero, 2023). In common bean progenies obtained from crosses carried out in East Africa was found a negative estimate of genetic gain for cooking time (Saradadevi et al., 2021). On the other hand, positive genetic gains were obtained for cooking time in carioca bean lines (Dias et al., 2021) and in the selection of white, yellow, cranberry, and carioca bean cultivars (Ribeiro et al., 2021), using selection indices. Therefore, the genetic gain for cooking time in common bean will vary according to the period of evaluation, estimation method, homozygosity level of the lines, genetic variability, and grain type analyzed.

Average cooking time in the evaluated common bean lines ranged from 15 min and 58 s (biennium 5) to 20 min and 56 s (biennium 2) (Table 4), indicating that most of the lines developed by the Southern Brazilian Common-Bean Network between the years 2010 and 2022 are fast-cooking, that is, they have a cooking time ≤ 25 min, according to the criteria established by Santos, Ribeiro and Maziero (2016). In the 2010s, several fast-cooking common bean lines were developed by the main breeding programs in Brazil (Santos; Ribeiro; Maziero, 2016; Kläsener; Ribeiro; Argenta, 2022; Ribeiro et al., 2023; Ribeiro; Maziero, 2023), evidencing success in reducing cooking time. The decrease in the cooking time can be associated with the lowest mass of 100 grains of the new common bean cultivars released for cultivation in the southern region of Brazil.

The fast-cooking reference for common bean in 1971, when cultivar Carioca was released for cultivation in Brazil, was 1 h and 35 min (Almeida; Leitão Filho; Miyasaka, 1971). In other words, after half a century of common bean breeding in Brazil, it was possible to reduce the cooking time of new cultivars by 1 h and 10 min. Therefore, the strategies used by breeding programs in Brazil were efficient in decreasing cooking time and gas consumption in the preparation of common bean, which is of great importance in the context of sustainability and food and nutritional security for consumers who use the common bean as their main source of dietary protein.

The genetic gain results show that the common bean lines developed by the Southern Brazilian Common-Bean Network between the years 2010 and 2022 had a decrease in mass of 100 grains and water absorption, but the L* value (lightness) of their grains and cooking time were unaltered (Table 3). The hypothesis is that selection for desirable technological quality traits, especially in carioca and black beans, may have resulted in erosion of genetic diversity, validating previous results described for Andean common bean (Trucchi et al., 2021). This may have been because cultivar Carioca started to be used as a parent in several common-bean breeding programs in Brazil due to its excellent agronomic and culinary traits

(Wutke; Almeida, 2017). As a consequence, less genetic diversity has been described for carioca bean cultivars (Almeida et al., 2020).

The magnitude and sign of the genetic gain estimates obtained in the present study for the technological grain quality traits were not favorable to the selection objectives of providing continuous and gradual improvements for these traits in the new common bean cultivars. However, it should be considered that most of the new common bean lines developed by the Southern Brazilian Common-Bean Network between the years 2010 and 2022 displayed adequate L* values for carioca (L* ≥ 53) and black (L* ≤ 22) bean grains, a mass of 100 grains from 20 to 25 g, and fast cooking (≤ 25 min). These traits provide high technological quality to the grains of the new common bean cultivars and are of great importance in the context of sustainability and food and nutritional security for the next generations. Despite this, the improvement of technological grain quality in common bean may have reached a plateau in Brazil due to the intense selection pressure that has been used to meet the quality standards demanded by sellers and consumers. In the medium and long term, the introgression of genes from wild, landrace, and Andean gene pool parental into carioca and black bean lines could provide genetic gains favorable to the technological grain quality traits of Mesoamerican common bean.

CONCLUSIONS

Mass of 100 grains and water absorption show negative genetic gains of -2.91% and -0.55% per year, respectively, whereas L* value (lightness) and cooking time exhibit zero genetic gain in common bean lines obtained for cultivation in southern Brazil. New common bean cultivars have high technological quality to the grains, i. e., adequate L* values for carioca (L* ≥ 53) and black (L* ≤ 22) beans, mass of 100 grains from 20 to 25 g, and fast cooking (≤ 25 min).

AUTHOR CONTRIBUTION

Conceptual idea: Ribeiro, N. D.; Methodology design: Ribeiro, N. D.; Maziero, S. M.; Argenta, H. S.; Data collection: Ribeiro, N. D.; Argenta, H. S.; Data analysis and interpretation: Maziero, S. M.; Ribeiro, N. D.; and Writing and editing: Ribeiro, N. D.

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