

Simultaneous selection for seed physiological quality traits in common bean cultivars under drought stress

Seleção simultânea para qualidade fisiológica de sementes em cultivares de feijão sob estresse com seca

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ABSTRACT - Selection for high seed germination and vigor under drought stress has received little attention in common bean breeding programs. In this context, the objectives of this study were to evaluate the phenotypic variability of common bean cultivars for seed physiological quality under drought stress, analyze the correlation among these traits, and select cultivars with high germination and vigor under such conditions. To this end, seeds of 25 common bean cultivars were produced over two growing seasons under drought stress. Seed physiological quality was assessed through the germination, first count, germination speed index, mass electrical conductivity, accelerated aging, and cold tests. Significant cultivar and cultivar $\times$ environment interaction effects were observed for all tests in the combined analysis of variance. The tests used allowed for differentiation among cultivars; however, they did not show complete agreement in identifying those with the highest seed physiological quality. Germination was not correlated with the germination speed index, mass electrical conductivity, accelerated aging, or cold tests. Therefore, the combined use of these five tests provides greater efficiency in selecting cultivars with high seed physiological quality under drought stress. The presence of phenotypic variability for seed germination and vigor favors simultaneous selection using the multiplicative index. Cultivars SCS 205 Riqueza, IPR Juriti, BRS Esplendor, IPR Tangará, and Fepagro 26 demonstrate high seed physiological quality under drought stress.

RESUMO - A seleção para alta germinação e vigor de sementes produzidas sob estresse com seca não tem recebido muita atenção pelos programas de melhoramento de feijão. Nesse contexto, foram objetivos deste estudo, avaliar a variabilidade fenotípica de cultivares de feijão para a qualidade fisiológica de sementes sob estresse com seca, analisar a correlação entre esses caracteres e selecionar cultivares com alta germinação e vigor sob estresse com seca. Para isso, sementes de 25 cultivares de feijão comum foram produzidas em duas épocas de cultivo em condições de estresse com seca. A qualidade fisiológica das sementes foi determinada pelos testes de germinação, primeira contagem, índice de velocidade de germinação, condutividade elétrica massal, envelhecimento acelerado e teste de frio. Para todos os testes foram observados efeitos significativos de genótipo e da interação genótipo $\times$ ambiente na análise de variância conjunta. Os testes usados possibilitaram a diferenciação das cultivares, entretanto não foram 100% concordantes na identificação das cultivares com maior qualidade fisiológica de sementes. A germinação não foi correlacionada com os testes de índice de velocidade de germinação, condutividade elétrica massal, envelhecimento acelerado e de frio. Por consequência, o uso combinado destes cinco testes permite maior eficiência na seleção de cultivares com alta qualidade fisiológica de sementes sob estresse com seca. A existência de variabilidade fenotípica para germinação e vigor das sementes é favorável a seleção simultânea pelo índice multiplicativo. As cultivares SCS 205 Riqueza, IPR Juriti, BRS Esplendor, IPR Tangará e Fepagro 26 mostram alta qualidade fisiológica de sementes sob estresse com seca.

Keywords: *Phaseolus vulgaris*. Genetic variability. Vigor. Multiplicative index.

Palavras-chave: *Phaseolus vulgaris*. Variabilidade genética. Vigor. Índice multiplicativo.

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INTRODUCTION

Food production under climate change is a major challenge for today's producers. Under these conditions, longer drought periods, higher temperatures, and lower precipitation are expected to occur more frequently (LOSA et al., 2022), thereby reducing crop yields. Aware of the devastating impacts of global warming on agriculture, breeding programs have concentrated efforts on developing drought-resilient cultivars.

Common bean (*Phaseolus vulgaris* L.) is one of the crops most vulnerable to drought stress in Brazil. Under drought stress, common bean genotypes showed limited reproductive development and a decrease in the number of days to maturity and in seed weight (PRADO-GARCÍA et al., 2025). Additionally, reductions in leaf area and grain yield (GONÇALVES et al., 2022), as well as in seed germination and vigor (KOCH et al., 2018; PADILHA; COELHO; SOMMER, 2022) have been reported in common beans. Breeding efforts have focused on increasing adaptation to drought conditions through gene introgression of *Phaseolus acutifolius* (BUITRAGO-BITAR et al., 2021; BURBANO-ERAZO et al., 2021) and crop wild relatives and landraces (CORTÉS; LÓPEZ-HERNÁNDEZ, 2021). As a result, higher scores for CO₂ assimilation, greater

water use efficiency (BURBANO-ERAZO et al., 2021), and preserved robust pod loading and seed development (PRADO-GARCÍA et al., 2025) were observed in drought-tolerant common bean genotypes.

Seed physiological quality refers to germination and vigor that is, the set of attributes determining the potential for rapid and uniform seedling emergence under a wide variety of environments (ISTA, 2014). Therefore, the use of seeds with high physiological quality is essential for achieving optimal plant populations and high grain yields.

Moreover, the most widely consumed grain types in the country, carioca (beige seed coat with brown streaks) and black, are produced in small quantities in other countries, which can lead to domestic supply shortages, particularly under climate change. Conversely, cranberry grain class (cream seed coat with red streaks) is not widely cultivated in Brazil, but there is high demand for exportation. Previous studies have reported variability in germination and vigor among common bean genotypes (MAMBRIN et al., 2015; GINDRI et al., 2017; GINDRI; COELHO, 2019; OLIVEIRA et al., 2020; PADILHA; COELHO; EHRHARDT-BROCADE, 2021; PADILHA; COELHO; SOMMER, 2022). Genotype $\times$ environment interactions have also been observed for seed physiological quality traits in this crop (PADILHA; COELHO; ANDRADE, 2020). However, no studies were found in the literature addressing the selection of common bean cultivars with high seed physiological quality from field experiments conducted under drought stress conditions. The hypothesis is that it is possible to differentiate common bean cultivars based on germination and vigor in seeds produced under drought-stressed field conditions.

In this context, simultaneous selection for multiple seed physiological quality traits in common bean can contribute significantly to progress in breeding programs aimed at drought resilience. Selecting drought-resilient cultivars is essential for ensuring sustainability and food and nutritional security for future generations. Therefore, the objectives of this study were to evaluate the phenotypic variability of common bean cultivars for seed physiological quality under drought stress, analyze the correlation among these traits, and select cultivars with high germination and vigor under such conditions.

MATERIAL AND METHODS

Growing conditions for acquiring the seeds used in the experiments

The seeds of the cultivars evaluated were obtained from the common bean germplasm bank at the Federal University of Santa Maria (UFSM), Santa Maria, Rio Grande do Sul (RS), Brazil. These seeds were multiplied in 2019 in a field area at UFSM (latitude 29°72' S, longitude 53°72' W, and altitude 95 m) to increase seed quantity.

With the aim of ensuring that all seeds of the evaluated cultivars were produced under similar conditions, sowing was carried out on November 20, 2019. The seeding density used was 15 seeds per linear meter. Management practices were similar to those employed by common bean producers in the southern region of Brazil. Seeds were harvested at approximately 18% moisture content.

Field experiments

The experiments took place in 2020 (sowing on October 9) and 2021 (sowing on February 23), during the rainy and dry seasons, respectively. These two growing seasons showed differences in relative humidity, maximum temperature, minimum temperature, and precipitation (Figure 1).

Both trials were also conducted in a field area at UFSM, which has a typic alitic Argisol (Hapludalf) soil. The region is characterized by a humid subtropical climate, with rainfall evenly distributed throughout the year. However, the years 2020 and 2021 were affected by the La Niña climate phenomenon (JONES, 2022). In the state of Rio Grande do Sul, this climate condition results in above-average annual temperatures, higher solar radiation levels, and below-average annual precipitation (MATZENAUER; RADIN; MALUF, 2017), causing drought stress.

Both experiments utilized a randomized complete block design with three replicates. Each experimental plot consisted of four 4-m-long rows, spaced 50 cm apart, with usable area of 4 m². Seeding density was adjusted according to the growth habit (GH) of each cultivar: 18, 15, and 12 seeds per linear meter were used for cultivars with types I (determinate GH), II (indeterminate GH with short branches), and III (indeterminate GH with long branches), respectively. The thinning of the plants was not carried out.

Treatments were 25 common bean cultivars registered for cultivation in Brazil over the past 40 years. Most cultivars originated from the Mesoamerican gene pool and represent the most widely produced commercial types in Brazil: carioca (IPR Siriri, IPR Tangará, IAC Milênio, BRSMG Pioneiro, Fepagro Garapiá, Pérola, IAC Imperador, IPR Juriti, SCS 205 Riqueza, and BRS Estilo) and black (IPR Uirapurú, IAC Netuno, BRS Esplendor, IPR Tuiuiú, BRS Valente, BRS Esteio, Fepagro 26, Guapo Brilhante, IPR Graúna, BRS Expedito, IPR Tiziu, Fepagro Triunfo, and BRS Campeiro). Two cultivars from the Andean gene pool Irai and BRSMG Realce, with cranberry beans were also analyzed.

All experiments were conducted under conventional cultivation, which consisted of one plowing and two harrowing operations for soil preparation. The soil analysis report revealed the following composition in 2020: pH (H₂O), 6.5; organic matter, 1.0%; K, 128.0 mg dm⁻³; P, 20.3 mg dm⁻³; Ca, 6.4 cmol dm⁻³; Mg, 3.1 cmol dm⁻³; and Zn, 0.68 mg dm⁻³. Fertilization was carried out with 200 kg ha⁻¹ of the 05-20-20 (N-P₂O₅-K₂O) formula applied on the day of sowing and 40 kg ha⁻¹ of nitrogen (urea source) broadcast in the crop row at the third trifoliate leaf stage. Weed and insect control followed standard technical recommendations for common bean cultivation.

Harvesting was performed manually at the maturity stage (R9), in which the days after sowing varied for each cultivar assessed and year evaluated. At R9, all cultivars exhibited seeds with approximately 18% moisture content. This step, along with seed processing, was done manually to avoid mechanical damage and cultivar mixing. Seeds were then dried to 13% moisture content and stored in kraft paper bags covered with plastic bags. These were kept in a cold chamber regulated at 0 °C and 70% relative humidity for approximately 30 days prior to seed physiological quality assessments.



Figure 1. Seasonal variation in rainfall, maximum temperature, minimum temperature, and relative humidity recorded at an automatic meteorological station during the 2020 rainy and 2021 dry seasons.

Determination of seed physiological quality traits

Seeds obtained from the usable area of the three replicates in each experiment were mixed and homogenized into a single 1,000 g sample per cultivar. From this sample, four subsamples of 250 g were randomly picked for germination and vigor assessments.

The germination test was implemented following the Rules for Seed Testing (BRASIL, 2025), using four replicates of 50 seeds. The test was carried out in a germinator set at a constant temperature of 25 °C. Germination was determined by counting the number of normal seedlings on the ninth day and expressing the result as a percentage. Normal seedlings were defined as those possessing essential structures: primary root, hypocotyl, epicotyl, cotyledons, and plumule.

Two vigor tests were performed during the germination test: first count and germination speed index (GSI). The first count represented the number of normal seedlings identified five days after the start of the germination test, converted to a percentage. The GSI was calculated by counting seeds with radicles longer than 3 cm each day of the test, using the following equation (Equation 1):

$$GSI = G1/N1 + G2/N2 + \dots + Gn/Nn \quad (1)$$

in which: GSI = germination speed index; G1, G2, ... Gn = number of seeds with radicle length > 3 cm on days 1, 2, ... n; N1, N2, ... Nn = evaluation day 1, 2, ... n.

Additionally, the following vigor tests were conducted: mass electrical conductivity, accelerated aging, and the cold test. The mass electrical conductivity test used four replicates of 25 seeds. Seeds were placed in plastic cups with 75 mL of deionized water and kept in a germinator at 20 °C for 24 h. The electrical conductivity of the solution was then measured with a conductivity meter (EC-150, Simple, China) and expressed in $\mu S \text{ cm}^{-1} \text{ g}^{-1}$ of seed.

The accelerated aging test was performed using four replicates of 50 seeds. Seeds were evenly distributed on a metal screen and placed inside an acrylic box (11.0 cm x 11.0 cm x 3.5 cm) containing 40 mL of distilled water. The boxes were kept in an air-circulating greenhouse at a constant temperature of 42 °C for 48 h. Following this, seeds were transferred to towel paper for germination and subjected to a standard germination test as recommended by Brasil (2025).

Finally, the cold test involved four replicates of 50 seeds each. Seeds were distributed on towel paper for

germination, and the rolls were stored vertically in a germinator set at a constant temperature of 10 °C for 72 h. After this period, the temperature was adjusted to 25 °C, in accordance with the germination test procedure. The number of normal seedlings was counted on the ninth day and expressed as a percentage.

Statistical analyses

Data were evaluated to confirm compliance with the assumptions of randomness, normality, and homoscedasticity of error. The normality of data was evaluated by the Shapiro-Wilk test, and homogeneity of residual variance was assessed using the Bartlett test, at a 5% probability level. These analyses were performed using Sisvar software (FERREIRA, 2011), and the other statistical analyses, using Genes software (CRUZ, 2016). Only the assumption of normality was not met for germination, first count, accelerated aging, and cold test data in both experiments. For these data, the following transformation was required (Equation 2):

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

in which: x : the trait value.

After transformation, all seed physiological quality traits met the model assumptions. The data were then subjected to a combined analysis of variance, adopting a completely randomized design with four replicates in which the following model was employed (Equation 3):

$$Y_{ijk} = m + C_i + E_j + CE_{ij} + \varepsilon_{ijk} \quad (3)$$

in which: Y_{ijk} = observed response for each trait, for cultivar i in environment j and replicate k ; m = overall mean; C_i = effect of cultivar i ; E_j = effect of environment j ; CE_{ij} = interaction between cultivar i and environment j ; ε_{ijk} = experimental error associated with the experimental unit.

In the combined analysis of variance, all effects were considered fixed, except for the error, which was treated as random. In this analysis, phenotypic variation was partitioned into cultivar, environment, cultivar $\times$ environment interaction, and error for all evaluated tests. The F-test was used to determine the significance of the main effects (cultivar and environment) and the cultivar $\times$ environment interaction (p -value < 0.05). Subsequently, the means for different cultivars were compared using the Scott-Knott test, and for growing seasons the t-test was employed at a 5% probability level.

Pearson's linear correlation coefficient was applied to assess the relationships among seed physiological quality traits. These coefficients were estimated from the matrix of means generated in the combined analysis of variance. The significance of the correlation coefficients was tested using Student's t-test at a 5% probability level.

Multicollinearity diagnostics were undertaken using the phenotypic correlation matrix derived from the combined analysis of variance. The magnitude of the condition number

defined the multicollinearity class, as proposed by Montgomery, Peck and Vining (2021).

Simultaneous selection was carried out using the multiplicative index (SUBANDI; COMPTON; EMPIG, 1973). To select the five common bean cultivars with the highest number of traits associated with superior seed physiological quality, emphasis was placed on the lowest values for mass electrical conductivity and the highest values for all other evaluated tests.

RESULTS AND DISCUSSION

Analysis of variance and partitioning of phenotypic variation

For all seed physiological quality traits, significant effects were found for cultivar and cultivar $\times$ environment interaction (p -value < 0.05) (Table 1). Previous studies similarly reported that common bean seed germination and vigor vary with genotype (MAMBRIN et al., 2015; OLIVEIRA et al., 2020; PADILHA; COELHO; EHRHARDT -BROCAO, 2021; SILVA et al., 2023) and with genotype $\times$ environment interaction (PADILHA; COELHO; ANDRADE, 2020). These findings indicate that germination and vigor tests properly differentiate common bean cultivars; however, several seed physiological quality traits are affected by the environment in which cultivars are grown.

The existence of genetic variability enables the selection of cultivars with high seed physiological quality. However, for this selection to be more effective, environmental variability across years, seasons, and/or growing locations must be considered an aspect that has not been prioritized in common bean breeding programs. Thus, partitioning phenotypic variation into cultivar, environment, cultivar $\times$ environment interaction, and error allows for a better understanding of how each source contributes to variability in seed physiological quality traits.

Cultivar was the main contributor to phenotypic variation for germination, first count, and mass electrical conductivity, indicating that these tests were minimally influenced by the environment. As such, these three tests may offer greater gains in selection for high seed physiological quality. However, the environment was the source of variation that most contributed to phenotypic variation for germination speed index and accelerated aging ($\geq 65.00\%$). Therefore, selection based on these two tests may yield smaller gains in improving seed vigor in common bean.

Conversely, the cultivar $\times$ environment interaction had the greatest influence on phenotypic variation in the cold test (54.99%). This suggests that selection for cold test performance should be based on multiple experiments. No previous studies have been found evaluating the predominance of cultivar, environment, or cultivar $\times$ environment effects on seed germination or vigor in common bean. In the present study, different sources of variation were more important for the phenotypic variability observed among common bean cultivars in the germination and vigor tests.

Table 1. Combined analysis of variance for germination, first count, germination speed index, mass electrical conductivity, accelerated aging, and cold tests evaluated in the 25 common bean cultivar seeds obtained in the 2020 rainy and 2021 dry growing seasons.

	DF ¹	Germination (%)		First count (%)		Germination speed index	
		MS ²	PV ³ (%)	MS	PV (%)	MS	PV (%)
Cultivar (C)	24	0.80 *	39.08	1.58 *	41.70	21.68 *	5.26
Environment (E)	1	0.00 ^{ns}	0.00	2.71 *	2.97	8573.95 *	86.66
C × E	24	0.71 *	34.41	1.32 *	34.74	17.72 *	4.30
Error	150	0.09	26.51	0.12	20.58	2.50	3.78
Mean		9.51		9.25		21.86	
CEV ⁴ (%)		3.10		3.82		7.23	
SA ⁵		0.94		0.96		0.94	
		Mass electrical conductivity (μS cm ⁻¹ g ⁻¹)		Accelerated aging (%)		Cold test (%)	
		MS	PV (%)	MS	PV (%)	MS	PV (%)
Cultivar (C)	24	57178.44 *	40.56	3.55 *	11.07	3.79 *	19.92
Environment (E)	1	215073.55 *	6.36	500.80 *	65.00	20.74 *	4.54
C × E	24	52449.28 *	37.20	4.18 *	13.02	10.46 *	54.99
Error	150	3582.54	15.88	0.56	10.90	0.62	20.54
Mean		428.47		7.27		7.52	
CEV (%)		13.97		10.29		10.51	
SA		0.97		0.92		0.91	

¹DF: degrees of freedom; ²MS: mean squares; ³PV: phenotypic variation; ⁴CEV: coefficient of experimental variation; ⁵SA: selective accuracy.

*Significant by the *F* test at 5% probability; ^{ns}Not significant.

Phenotypic variability for seed physiological quality traits

Germination rates among the common bean cultivars ranged from 65.50 (BRS Esplendor, dry season) to 100.00% (Fepagro Triunfo, dry season) (Table 2). A similar range of variation in germination has been reported for common bean genotypes (MAMBRIN et al., 2015; GINDRI et al., 2017; GINDRI; COELHO, 2019), supporting the feasibility of selecting cultivars with high germination. However, cultivars Iraí, BRS Valente, IPR Graúna, BRS Expedito, IPR Tiziu, Fepagro Triunfo, IPR Siriri, IAC Milênio, and IPR Juriti were identified as having high germination ($\geq 90.00\%$) in both growing seasons. When common bean cultivars were grown over two consecutive years, one cultivar was found to stand out for its high germination in both years (PADILHA; COELHO; ANDRADE, 2020). These findings suggest that it is possible to develop new common bean cultivars that maintain high germination across multiple environments.

In the context of climate change, improving drought resilience has been the main challenge for breeding programs. This is because under drought stress simulated in the laboratory with polyethylene glycol, reductions in seed germination and vigor have been observed in common bean (KOCH et al., 2018; PADILHA; COELHO; SOMMER, 2022). Under drought conditions the cycle was significantly shortened in common bean plants, with maturity advanced by five days, indicating an effective escape mechanism that sacrifices productive potential to complete the reproductive cycle (PRADO-GARCÍA et al., 2025). No studies evaluating common bean seed physiological quality under natural drought stress in field conditions were found in the literature. Therefore, investigating how drought stress affects seed germination and vigor under field conditions is of great

importance for ensuring food and nutritional security.

In the present study, nine cultivars Iraí, BRS Valente, IPR Graúna, BRS Expedito, IPR Tiziu, Fepagro Triunfo, IPR Siriri, IAC Milênio, and IPR Juriti exhibited high germination ($\geq 90.00\%$) in both drought-stressed seasons (Table 2), demonstrating greater drought resilience. Conversely, BRSMG Realce and IAC Netuno in the 2020 rainy season and IAC Netuno, BRS Esplendor, and Fepagro Garapiá in the 2021 dry season showed germination below 80%, indicating lower drought resilience. These four cultivars failed to meet the minimum 80% germination standard required for the sale of common bean seed in Brazil (BRASIL, 2013) when produced under drought stress conditions. These results confirm the potential for selecting drought-resilient common bean cultivars and highlight the important role of breeding programs in improving seed physiological quality under drought conditions.

The five vigor tests analyzed enabled the differentiation of common bean cultivars. However, these tests did not fully agree in classifying cultivars with high vigor for each growing season or in both seasons (Tables 2 and 3). The following cultivars exhibited high vigor in the first count test in the two growing seasons: BRS Valente, IPR Graúna, BRS Expedito, Fepagro Triunfo, IPR Tangará, IAC Milênio, and IPR Juriti (Table 2). In the germination speed index test, cultivars IPR Uirapurú, BRS Esplendor, Fepagro 26, Fepagro Triunfo, IAC Milênio, Fepagro Garapiá, IAC Imperador, IPR Juriti, and SCS 205 Riqueza stood out for their high vigor in both growing seasons. High-vigor common bean genotypes were identified in both the first count test (MAMBRIN et al., 2015; MEDEIROS et al., 2019; PADILHA; COELHO; SOMMER, 2022) and the germination speed index test (PADILHA; COELHO; ANDRADE, 2020;

PADILHA; COELHO; EHRHARDT-BROCADO, 2021). However, it is important to note that these tests are conducted under controlled laboratory conditions; therefore, the high seed vigor observed in these genotypes may not be confirmed under field conditions.

The electrical conductivity test made it possible to stratify common bean cultivars into a greater number of classes in both growing seasons (Table 3), indicating its greater sensitivity for assessing seed vigor. In this test, lower electrical conductivity values indicate higher seed vigor, as a lower amount of leachates in the solution is associated with better cell membrane integrity (BINOTTI et al., 2008). The cultivars that showed high vigor in the 2020 rainy season crop were IPR Graúna, IPR Juriti, and SCS 205 Riqueza, differing

significantly from the remaining cultivars. In the 2021 dry season crop, a larger number of cultivars stood out by the high vigor in this test, namely, IPR Uirapurú, IAC Netuno, BRS Esplendor, IPR Tuiuiú, BRS Esteio, Fepagro 26, IPR Tangará, IAC Milênio, IAC Imperador, IPR Juriti, SCS 205 Riqueza, and BRS Estilo. The electrical conductivity test has proven effective for differentiating common bean seeds both between lots of the same cultivar (MEDEIROS et al., 2019) and between genotypes in terms of vigor (GINDRI et al., 2017; ORTIZ et al., 2018). It is also a good indicator of seedling emergence in the field because, according to Binotti et al. (2008) it is based on cell membrane integrity and analyzes changes in seed metabolism.

Table 2. Mean* values obtained for germination, first count, and germination speed index tests of the 25 common bean cultivar seeds obtained in the 2020 rainy (rainy) and 2021 dry (dry) growing seasons.

Cultivars	Germination (%)		First count (%)		Germination speed index	
	Rainy	Dry	Rainy	Dry	Rainy	Dry
Cranberry beans						
BRSMG Realce	79.00 bB	92.50 bA	77.00 bA	89.50 bA	21.83 cA	15.01 bB
Iraí	94.50 aA	94.00 aA	82.00 bA	92.50 aA	24.61 bA	14.75 bB
Black beans						
IPR Uirapurú	89.50 aA	82.50 cA	89.50 aA	55.50 dB	29.21 aA	16.21 aB
IAC Netuno	76.00 bA	72.50 dA	74.50 bA	54.00 dB	28.19 aA	13.17 cB
BRS Esplendor	99.00 aA	65.50 eB	95.50 aA	63.75 cB	33.71 aA	16.76 aB
IPR Tuiuiú	80.50 bB	97.50 aA	79.50 bB	97.00 aA	26.81 bA	16.95 aB
BRS Valente	96.00 aA	97.50 aA	96.00 aA	91.50 aA	30.54 aA	15.74 bB
BRS Esteio	82.50 bA	94.00 aA	80.00 bA	72.50 cA	25.04 bA	17.03 aB
Fepagro 26	87.50 bA	85.00 cA	86.50 aA	84.00 bA	29.96 aA	17.28 aB
Guapo Brilhante	97.00 aA	89.00 bA	96.00 aA	84.00 bA	26.36 bA	12.01 cB
IPR Graúna	90.00 aA	96.50 aA	88.00 aA	95.00 aA	26.46 bA	12.99 cB
BRS Expedito	93.50 aA	99.00 aA	92.00 aA	98.50 aA	30.54 aA	12.85 cB
IPR Tiziu	97.50 aA	96.50 aA	89.50 aA	88.00 bA	30.38 aA	10.35 dB
Fepagro Triunfo	95.50 aA	100.00 aA	91.50 aA	99.00 aA	31.50 aA	16.48 aB
BRS Campeiro	92.00 aA	81.00 cA	91.50 aA	65.00 cB	28.75 aA	15.52 bB
Carioca beans						
IPR Siriri	94.50 aA	96.50 aA	93.00 aA	87.50 bA	28.63 aA	15.46 bB
IPR Tangará	88.00 bA	98.00 aA	85.50 aA	93.50 aA	26.63 bA	16.63 aB
IAC Milênio	94.00 aA	97.50 aA	90.50 aA	96.00 aA	29.50 aA	16.56 aB
BRSMG Pioneiro	83.50 bA	87.50 bA	79.00 bA	78.75 bA	30.59 aA	14.97 bB
Fepagro Garapiá	94.00 aA	74.00 dB	89.50 aA	69.00 cB	28.98 aA	16.39 aB
Pérola	87.50 bA	95.50 aA	87.00 aA	81.00 bA	27.31 bA	12.96 cB
IAC Imperador	87.00 bA	82.00 cA	85.50 aA	69.00 cB	29.69 aA	16.95 aB
IPR Juriti	95.00 aA	99.50 aA	93.50 aA	97.50 aA	30.10 aA	16.84 aB
SCS 205 Riqueza	96.00 aA	90.00 bA	93.50 aA	88.00 bA	28.44 aA	16.18 aB
BRS Estilo	84.50 bB	96.50 aA	83.00 bB	94.50 aA	26.42 bA	16.74 aB
Mean	82.50	90.62	87.66	83.69	28.41	15.31
CEV (%) ¹	3.60	2.51	4.20	3.37	7.08	6.35
SA ²	0.86	0.98	0.81	0.98	0.92	0.97

* Means not followed by the same lowercase letter in the column differ by the Scott-Knott test, and uppercase letters in each row by the t-test, at 5% probability.

¹CEV (%) = coefficient of experimental variation; ²SA = selective accuracy.

Table 3. Mean* values obtained for mass electrical conductivity, accelerated aging, and cold tests of the 25 common bean cultivar seeds obtained in the 2020 rainy (rainy) and 2021 dry (dry) growing seasons.

Cultivars	Mass electrical conductivity ($\mu\text{S cm}^{-1} \text{ g}^{-1}$)		Accelerated aging (%)		Cold test (%)	
	Rainy	Dry	Rainy	Dry	Rainy	Dry
Cranberry beans						
BRSMG Realce	440.84 cA	437.31 cA	84.00 aA	32.50 bB	45.00 cB	76.00 aA
Iraí	457.17 cA	434.81 cA	67.50 bA	29.00 cB	76.50 aA	67.00 aA
Black beans						
IPR Uirapurú	569.50 aA	244.56 eB	77.50 aA	39.50 bB	73.50 aA	43.00 dB
IAC Netuno	481.50 bA	312.56 eB	59.00 bA	27.00 cB	80.00 aA	18.00 eB
BRS Esplendor	455.17 cA	240.81 eB	83.50 aA	60.50 aA	53.00 cA	60.50 bA
IPR Tuiuiú	519.50 aA	262.56 eB	61.50 bA	52.50 aA	65.50 bA	69.50 aA
BRS Valente	488.17 bA	526.81 cA	83.00 aA	38.00 bB	66.50 bA	48.50 cB
BRS Esteio	511.50 bA	274.06 eB	66.00 bA	23.00 cB	56.00 cB	85.00 aA
Fepagro 26	469.84 bA	224.56 eB	79.50 aA	19.00 dB	68.50 bA	64.50 bA
Guapo Brilhante	442.50 cA	647.31 bB	88.50 aA	11.00 dB	89.00 aA	35.50 dB
IPR Graúna	380.50 dB	530.81 cA	85.00 aA	52.00 aB	80.50 aA	18.00 eB
BRS Expedito	445.17 cB	643.75 bA	88.00 aA	57.00 aB	89.00 aA	27.50 eB
IPR Tiziu	488.84 bB	574.81 cA	70.85 bA	33.00 bB	71.00 bA	26.50 eB
Fepagro Triunfo	455.50 cA	532.56 cA	80.00 aA	45.50 bB	70.50 bA	45.50 cB
BRS Campeiro	439.17 cA	408.56 dA	78.50 aA	34.50 bB	76.00 aA	77.50 aA
Carioca beans						
IPR Siriri	420.50 cA	389.81 dA	88.50 aA	12.50 dB	62.50 bA	36.50 dB
IPR Tangará	491.84 bA	282.06 eB	66.00 bA	50.50 aA	60.50 bB	81.00 aA
IAC Milênio	493.17 bA	276.06 eB	78.00 aA	19.50 dB	31.00 dB	64.00 bA
BRSMG Pioneiro	488.17 bA	496.56 cA	76.00 aA	16.50 dB	45.50 cA	47.50 cA
Fepagro Garapiá	447.84 cA	343.31 dB	85.50 aA	15.00 dB	65.00 bA	62.50 bA
Pérola	534.50 aB	783.06 aA	84.00 aA	23.50 cB	52.50 cA	22.50 eB
IAC Imperador	420.84 cA	298.81 eB	79.15 aA	40.00 bB	54.00 cA	64.00 bA
IPR Juriti	365.50 dA	226.81 eB	88.66 aA	29.00 cB	30.50 dB	80.00 aA
SCS 205 Riqueza	403.84 dA	207.31 eB	83.67 aA	59.00 aB	61.50 bA	59.00 bA
BRS Estilo	420.50 cA	292.31 eB	76.29 aA	35.50 bB	41.50 cB	73.50 aA
Mean	461.26	395.68	78.04	34.20	63.14	54.12
CEV (%) ¹	7.92	19.29	5.02	16.87	9.94	11.13
SA ²	0.92	0.97	0.90	0.93	0.93	0.97

* Means not followed by the same “lowercase letter” in the column differ by the Scott-Knott test, and uppercase letters in each row by the t-test, at 5% probability.

¹CEV (%) = coefficient of experimental variation; ²SA = selective accuracy.

Cultivars IPR Juriti and SCS 205 Riqueza were the most resilient to drought (high vigor), while cultivar Pérola was the least resilient (low vigor) under drought stress in both growing seasons, according to the electrical conductivity test (Table 3). Based on the dataset, the electrical conductivity test allowed the clearest differentiation among cultivars in terms of vigor. Additionally, it has been the most commonly used test for analyzing seed physiological quality due to its simplicity, quick turnaround, and ease of interpretation (AMARO et al., 2015; MAMBRIN et al., 2015; ORTIZ et al., 2018). These advantages favor its use in common bean breeding programs, especially in stages involving a large number of lines to be evaluated for seed vigor.

The accelerated aging and cold tests also made it possible to differentiate the cultivars into different vigor classes (Table 3). In the accelerated aging test, four cultivars showed high vigor in both growing seasons: BRS Esplendor, IPR Graúna, BRS Expedito, and SCS 205 Riqueza. This test has proven effective in stratifying the vigor of common bean seeds from different lots of the same cultivar (MEDEIROS et al., 2019) and among genotypes under cultivation (MAMBRIN et al., 2015; GINDRI et al., 2017; GINDRI; COELHO, 2019; PADILHA; COELHO; ANDRADE, 2020). Because the accelerated aging test exposes seeds to a high temperature (42 °C) during its initial phase, it was expected to be more sensitive for assessing vigor under drought stress

conditions. However, this expectation was not confirmed, as the environment contributed a high percentage of the phenotypic variation observed in this test (Table 1).

In the cold test, cultivars Irai and BRS Campeiro were among those classified as high-vigor in the two growing seasons under drought stress (Table 3). This test enabled the grouping of genotypes into different vigor classes when seeds were produced under conventional and organic cultivation systems (GINDRI et al., 2017). Although the cold test has been infrequently used in research to assess common bean seed vigor, it shows promise as an indicator of seedling emergence in the field under low-temperature conditions due to the initial exposure of seeds to low temperature (10 °C). For the cultivars assessed in this study, most of the phenotypic variation in the cold test was attributed to the cultivar × environment interaction (Table 1), suggesting that evaluating seeds from different production environments will enhance the efficiency of selecting high-vigor cultivars using the cold test.

The results of this study revealed phenotypic variability in the physiological quality traits of common bean seeds (Table 1). Furthermore, the germination and vigor tests distinguished cultivars under drought stress conditions (Tables

2 and 3). However, these tests did not fully agree in identifying the cultivars with the highest seed physiological quality under such conditions.

Correlation analysis of seed physiological quality traits

The correlation analysis between germination and vigor tests is essential to identify the most promising tests for distinguishing common bean cultivars in terms of seed physiological quality. A strong positive correlation ($r = 0.90$) was observed between germination and first count (Table 4), confirming that these two evaluations are highly associated in common bean seeds (AMARO et al., 2015; MAMBRIN et al., 2015). This correlation can be explained by the fact that both measurements were obtained from the same test: normal seedlings were counted at five days (first count) and at nine days (germination). The strong correlation between germination and first count indicates that these tests provide redundant information, and it is therefore unnecessary to perform both. In this case, only the germination test is recommended for evaluating the commercial quality of common bean seeds.

Table 4. Pearson's correlation coefficients obtained between the traits of germination (G), first count (FC), germination speed index (GSI), mass electrical conductivity (MEC), accelerated aging (AA), and cold (C) tests measured in 25 common bean cultivar seeds evaluated in the two growing seasons of 2020 and 2021.

	Pearson's correlation				
	FC	GSI	MEC	AA	C
G	0.90 *	-0.07 ^{ns}	0.28 ^{ns}	0.19 ^{ns}	-0.09 ^{ns}
FC		0.03 ^{ns}	0.17 ^{ns}	0.29 ^{ns}	-0.07 ^{ns}
GSI			-0.45 *	0.24 ^{ns}	0.11 ^{ns}
MEC				-0.11 ^{ns}	-0.39 *
AA					0.07 ^{ns}

*Significant by the test t at 5% probability; ^{ns}Not significant.

The mass electrical conductivity test showed a weak negative correlation with germination speed index ($r = -0.45$) and the cold test ($r = -0.39$). A similar low-magnitude negative correlation between electrical conductivity and germination speed index was reported in common bean seed lots (AMARO et al., 2015). Given the low correlations observed between mass electrical conductivity, germination speed index, and cold test, there are no restrictions on using these three tests together for assessing the physiological quality of common bean seeds.

No significant correlations were found among the other tests. Germination was not correlated with the germination speed index, mass electrical conductivity, accelerated aging, or cold tests. Therefore, the simultaneous use of these five tests is recommended for selecting common bean cultivars with high seed physiological quality under drought stress, as they provide complementary information.

Simultaneous selection for high seed physiological quality

Multicollinearity diagnostics showed a condition number of 24.34, revealing weak multicollinearity according to the classification proposed by Montgomery, Peck and

Vining (2021). This result shows that the variables are not strongly interrelated, justifying the inclusion of all tests in the simultaneous selection process.

High heritability estimates ($\geq 83.50\%$) were detected for all tests (Table 5), confirming the existence of phenotypic variation in seed quality among common bean cultivars (Tables 1, 2, and 3). Germination was the only trait for which no selection gain was observed (Table 5), but favorable selection gains were recorded for all other vigor tests. Gains with favorable signs for selection have also been reported for traits associated with seed physiological quality in snap beans (OLIVEIRA et al., 2020). The existing genetic variability for germination and seed vigor in common bean indicates the possibility of achieving greater gains by selecting drought-resilient cultivars.

Application of the multiplicative index led to the selection of cultivars SCS 205 Riqueza, IPR Juriti, BRS Esplendor, IPR Tangará, and Fepagro 26, which exhibited superior seed physiological quality under drought stress. IPR Juriti stood out for its highest germination rate (97.25%) and superior vigor as assessed by first count (95.50%) and lower mass electrical conductivity (296.16 $\mu\text{S cm}^{-1} \text{g}^{-1}$). SCS 205 Riqueza and IPR Tangará also showed high germination and

first count values, with IPR Tangará achieving the best performance in the cold test (70.75%). Although BRS Esplendor and Fepagro 26 displayed germination rates close to the minimum threshold of 80% established for the sale of common bean in Brazil (BRASIL, 2013), BRS Esplendor was

distinguished by its performance in the germination speed index (25.23) and accelerated aging (72.00%) tests. The use of the vigor test through different methodologies enhanced the efficiency of selecting cultivars with high seed physiological quality under drought stress.

Table 5. Mean of the original population (X_o), mean of selected cultivars (X_s), heritability (h^2), genetic gain (GG), and percentage of genetic gain (GG%) with simultaneous selection by the multiplicative index for germination (G), first count (FC), germination speed index (GSI), mass electrical conductivity (MEC), accelerated aging (AA), and cold (C) tests evaluated in the five common bean cultivars selected in the two growing seasons of 2020 and 2021.

	X_o	X_s	h^2 %	GG	GG %	Selected cultivars				
						SCS 205 Riqueza	IPR Juriti	BRS Esplendor	IPR Tangará	Fepagro 26
G	86.56	90.35	89.14	-0.00	-0.01	93.00	97.25	82.25	93.00	86.25
FC	85.89	88.13	92.10	0.13	1.37	90.75	95.50	79.62	89.50	85.25
GSI	21.86	22.87	88.49	1.23	5.64	22.31	23.47	25.23	21.63	23.62
MEC	428.47	336.77	93.73	-85.95	-20.06	305.57	296.16	347.99	386.95	347.20
AA	58.51	61.93	84.25	0.36	4.93	71.33	58.83	72.00	58.25	49.25
C	58.19	61.90	83.50	0.24	3.24	60.25	55.25	56.75	70.75	66.50

Simultaneous selection for multiple seed physiological quality traits has been underexplored in breeding programs. The rank sum index has been adopted to classify genotypes into seed quality categories (GINDRI et al., 2017; GINDRI; COELHO, 2019), but no previous studies were found employing simultaneous selection for seed physiological quality traits in field-grown common bean under drought conditions.

In the present study, five common bean cultivars were selected SCS 205 Riqueza, IPR Juriti, BRS Esplendor, IPR Tangará, and Fepagro 26, which exhibited high germination and vigor when grown under drought stress, standing out as the most drought-resilient. The cultivation of more drought-resilient cultivars will be crucial to promote faster seedling emergence, improved seedling uniformity in the field, greater plant population, and increased grain yield under climate change scenarios.

CONCLUSIONS

Common bean cultivars grown under drought stress showed phenotypic variability in seed physiological quality. The germination, germination speed index, mass electrical conductivity, accelerated aging, and cold tests are not correlated; thus, their combined use improves the efficiency of selecting common bean cultivars with high germination and vigor under drought stress. Cultivars SCS 205 Riqueza, IPR Juriti, BRS Esplendor, IPR Tangará, and Fepagro 26 exhibit high seed physiological quality under drought conditions.

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