SciELO Preprints

Publication status: This preprint has not been published elsewhere.

Environmental factors in G×E interaction and in specific genotype recommendations in common bean

Vilmar de Araújo Pontes Júnior, Patrícia Guimarães Santos Melo, Helton Santos Pereira, Eduardo Almeida Alves, Leonardo Cunha Melo

https://doi.org/10.1590/0103-8478cr20260049

Submitted on: 2026-11-26
Posted on: 2026-11-27 (version 1)
(YYYY-MM-DD)

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

Ciência Rural, Santa Maria, v.57:2, e20260049, 2027 http://doi.org/10.1590/0103-8478cr20260049

ISSNe 1678-4596
CROP PRODUCTION

Environmental factors in G×E interaction and in specific genotype recommendations in common bean

Vilmar de Araújo Pontes Júnior[1*] https://orcid.org/0009-0001-7870-4409
Patrícia Guimarães Santos Melo[2] https://orcid.org/0000-0001-5629-7489
Helton Santos Pereira[1] https://orcid.org/0000-0001-5348-7615
Eduardo Almeida Alves[2] https://orcid.org/0000-0001-9085-0292
Leonardo Cunha Melo[1] https://orcid.org/0000-0003-3862-2051

[1]Melhoramento Genético de Feijão, Embrapa Arroz e Feijão, 75375-000, Santo Antônio de Goiás, GO, Brasil. E-mail: vilmarpjr@gmail.com.
[*]Corresponding author.
[2]Escola de Agronomia, Universidade Federal de Goiás (UFG), Campus Samambaia, Goiânia, GO, Brasil.

Fatores ambientais na interação G×A e em recomendações específicas de genótipos de feijão-comum

Received 02.01.26 Approved 09.08.26 Returned by the author xx.xx.xx
CR-2026-0049.R1
Editors: Leandro Souza da Silva Alberto Cargnelutti Filho

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

Ciência Rural, Santa Maria, v.57:2, e20260049, 2027 http://doi.org/10.1590/0103-8478cr20260049
ISSNe 1678-4596
CROP PRODUCTION

Environmental factors in G×E interaction and in specific genotype recommendations in common bean

Vilmar de Araújo Pontes Júnior[1*] **Patrícia Guimarães Santos Melo**[2] **Helton Santos Pereira**[1] **Eduardo Almeida Alves**[2] **Leonardo Cunha Melo**[1]

[1]Melhoramento Genético de Feijão, Embrapa Arroz e Feijão, 75375-000, Santo Antônio de Goiás, GO, Brasil. E-mail: vilmarpjr@gmail.com.
[*]Corresponding author.
[2]Escola de Agronomia, Universidade Federal de Goiás (UFG), Campus Samambaia, Goiânia, GO, Brasil.

ABSTRACT: The wide diversity of environmental conditions under which common beans are cultivated requires understanding of the environmental effects of Locations, Seasons, and Years, to ensure reliability in cultivar recommendations. The goal was to decompose the interaction of Genotypes (G) with the environmental factors Locations (L), Seasons (S), and Years (Y), and to assess the relative importance of each factor across three cultivar recommendation regions in Brazil (RI – Center-South, RII – Central, and RIII – Northeast). Grain yield data from lines and cultivars of the carioca and black bean groups were analyzed, totaling 501 trials—207 in RI, 202 in RII, and 92 in RIII—conducted over a period of nine years for RI and RIII and eleven years for RII. The experimental sites represent the wide range of environmental conditions to which the crop is subjected in Brazil. A randomized complete block design was used, with three replications and plots of four four-meter rows. The coefficient of determination (R^2) was estimated to identify the contribution of each source of variation. Results indicated that the R^2 contribution of genotypes within each recommendation region, for both the carioca and black groups, was lower than that of Years and Seasons. The G×L interaction was the most important across all three regions for both grain types, compared to G×S and G×Y interactions. Therefore, in RI, RII, and RIII, priority should be given to increasing the number of evaluation sites, rather than of Seasons and Years, to achieve more efficient and reliable recommendations of new cultivars.
Key words: *Phaseolus vulgaris* L., cultivar recommendations, multi-environment trials.

Fatores ambientais na interação G×A e em recomendações específicas de genótipos de feijão-comum

RESUMO: A ampla diversidade de condições ambientais sob as quais o feijão-comum é cultivado requer a compreensão dos efeitos ambientais de Locais, Safras e Anos, a fim de assegurar a confiabilidade nas recomendações de cultivares. Nesse sentido, o objetivo deste estudo foi decompor a interação dos Genótipos (G) com os fatores ambientais de Locais (L), Safras (S) e Anos (Y), a fim de avaliar a importância relativa de cada fator em três regiões de recomendação de cultivares no Brasil (RI – Centro-Sul, RII – Central e RIII – Nordeste). Para realizar o objetivo, foram analisados dados de produtividade de grãos de linhagens e cultivares dos grupos carioca e preto, totalizando 501 ensaios, sendo 207 em RI, 202 em RII e 92 em RIII, conduzidos ao longo de nove anos em RI e RIII e onze anos em RII. Os locais experimentais representam a ampla faixa de condições ambientais às quais a cultura é submetida no Brasil. Além disso, utilizou-se o delineamento em blocos casualizados, com três repetições e parcelas compostas por quatro linhas de quatro metros. O coeficiente de determinação (R^2) foi estimado para identificar a contribuição de cada fonte de variação. Os resultados indicaram que a contribuição do R^2 dos genótipos dentro de cada região de recomendação, para ambos os grupos (carioca e preto), foi menor do que a de Anos e Safras. A interação G×L foi a mais importante nas três regiões para ambos os tipos de grão, em comparação às interações G×S e G×Y. Portanto, em RI, RII e RIII, deve-se priorizar o aumento do número de locais de avaliação, em vez do número de safras e anos, para alcançar recomendações mais eficientes e confiáveis de novas cultivares.
Palavras-chave: *Phaseolus vulgaris* L., recomendação de cultivares, ensaios multiambientes.

INTRODUCTION

Common bean is cultivated in almost all Brazilian States, across three sowing seasons (rainy, dry, and winter) and under distinct technological levels (MELO et al., 2018). In the presence of variability among genotypes and environments, average phenotypic responsiveness differs, generating a prominent interaction effect (TORGA et al., 2013a; LIMA et al., 2014). To address genotype × environment interactions, approaches such as agronomic zoning, stability estimation, or regionalized recommendations can be adopted (DUARTE & VENCOVSKY, 1999).

PEREIRA et al. (2010a) identified four cultivar recommendation regions with approximately homogeneous conditions for bean cultivation in Brazil. Among these, Region I (Center-South) accounts for 48.4% of production, concentrated in the rainy (October to December) and dry (February to March) sowing seasons,

Received 02.01.26 Approved 09.08.26 Returned by the author xx.xx.xx
CR-2026-0049.R1
Editors: Leandro Souza da Silva Alberto Cargnelutti Filho

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

with an average yield of 1773 kg ha^{-1}. Region II (Central) represents 50.9% of production, with an average yield of 1422 kg ha^{-1}, distributed across the rainy and winter (April to July) seasons. Region III (Northeast) accounts for 0.3% of production, with an average yield of 531 kg ha^{-1}—below the national average—and sowing occurs during the rainy season (February to April) (EMBRAPA ARROZ E FEIJÃO, 2024).

Environments factors are defined by the combination of different Seasons, Locations, and Years of cultivation that represent planting conditions. In this context, multiple trials across distinct environments allow a reliable and representative estimation of genotype × environment interaction and its components. For common bean, capturing this interaction requires a large number of final trials conducted in a network across multiple environments. The configuration of VCU (Value for Cultivation and Use) trial networks in different crop species is even regulated by the Brazilian Ministry of Agriculture (BRASIL, 2006).

To optimize the number of trials while capitalizing on the interaction effects, decomposition of genotype × environment interaction can be performed. For common bean, studies have been conducted in the states of Paraná and Santa Catarina (PEREIRA et al., 2010b; TORGA et al., 2013b; BALDIN et al., 2021), Minas Gerais (RAMALHO et al. 1998), Goiás and the Federal District (PEREIRA et al., 2011; TORGA et al., 2013a; MELO et al., 2018), Pernambuco (PEREIRA et al. 2013), and Rio de Janeiro (SOUZA et al., 2023; AMBRÓSIO et al., 2024). These studies indicated that environmental factors and their interactions significantly influence phenotypic responses.

Most decomposition studies lack a sufficient number of final trials and cover only a few producing regions. Moreover, analyses encompassing a longer period have not yet been conducted for the three main bean-producing regions in Brazil. The relevance of such research lies in its potential to provide substantial information and to identify new criteria for improving genotype evaluation, considering the effects of interactions between lines and environmental factors—such as Location, Season, and Year—with the aim of maximizing production efficiency.

Therefore, the objective of this study was to decompose genotype × environment interactions with respect to the environmental factors of Location, Season, and Year, to assess the relative importance of each within the three main cultivar recommendation regions, over eleven years of the common bean breeding program for carioca and black grain types conducted by Embrapa.

MATERIALS AND METHODS

Grain yield data were obtained from the common bean breeding program of Embrapa's VCU (Value for Cultivation and Use) trial network. A total of 88 genotypes (76 lines and 12 checks) from the carioca group were evaluated across 258 trials, and 71 genotypes (58 lines and 13 checks) from the black group across 243 trials, totaling 159 genotypes and 501 trials. The distribution of experiments followed the cultivar recommendation regions, as suggested by PEREIRA et al. (2010a): Region I (RI) comprised 107 carioca and 100 black bean trials; Region II (RII) included 105 carioca and 97 black bean trials; and Region III (RIII) comprised 46 carioca and 46 black bean trials.

Final trials were conducted between 2001 and 2012, encompassing six evaluation cycles: Cycle 1 – 2001/2002 (C1); Cycle 2 – 2003/2004 (C2); Cycle 3 – 2005/2006 (C3); Cycle 4 – 2007/2008 (C4); Cycle 5 – 2009/2010 (C5); and Cycle 6 – 2011/2012 (C6). For RII, all cycles were included, while RI and RIII did not include C1.

A randomized complete block design was used, with three replications. Each plot consisted of four 4-meter rows (8 m^2), with grain yield (kg ha^{-1}) evaluated from the two central rows only (4 m^2) (BRASIL, 2006). Fertilization was performed according to the results of soil analyses for each experimental area, and pest control and irrigation (during the winter season) were applied when necessary.

Individual and combined analyses of variance were performed for grain yield, with combined analyses conducted separately for each recommendation region: RI (rainy and dry seasons) and RII (rainy and winter seasons). Data was included from locations with evaluations in at least one season and two years (per biennial cycle), resulting in a partially balanced design. For RIII, with only one season per year, (rainy season), combined analyses were balanced, as data were obtained from locations evaluated in two years.

Selective accuracy (SA) was estimated according to RESENDE & DUARTE (2007) to assess the quality of individual experiments and classified as very high (SA $\geq$ 0.90), high (0.70 $\leq$ SA $<$ 0.90), moderate (0.50 $\leq$ SA $<$ 0.70), or low (SA $<$ 0.50) (RESENDE & DUARTE, 2007; CARGNELUTTI-FILHO et al. 2009).

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

Genotype (G), Location (L), Season (S), and Year (Y) effects were considered fixed. The decomposition of genotype × environment interaction in RI and RII was performed to isolate the effects of G×L, G×S, and G×Y, whereas in RIII only G×L and G×Y were considered.

To determine the relative importance of each source of variation the coefficient of determination (R^2) was estimated, following (RAMALHO et al., 1998; PEREIRA et al., 2011, 2013; TORGA et al., 2013a; 2013b; FERREIRA et al., 2015; PEREIRA et al., 2017). The coefficient of determination (R^2) was calculated as follows:

$$R_i^2 = \frac{SS_i}{SS_t} * 100$$

where SS_i is the sum of squares of source i and SS_t is the total sum of squares. The importance of each factor within the interaction was assessed based on the magnitude of R^2 values. For the figures (Figure 1A and Figure 1B), the values were calculated excluding the residual sum of squares, while including all the others factors.

Spearman's rank correlation coefficients were estimated among mean grain yield values using balanced data for each region, considering the

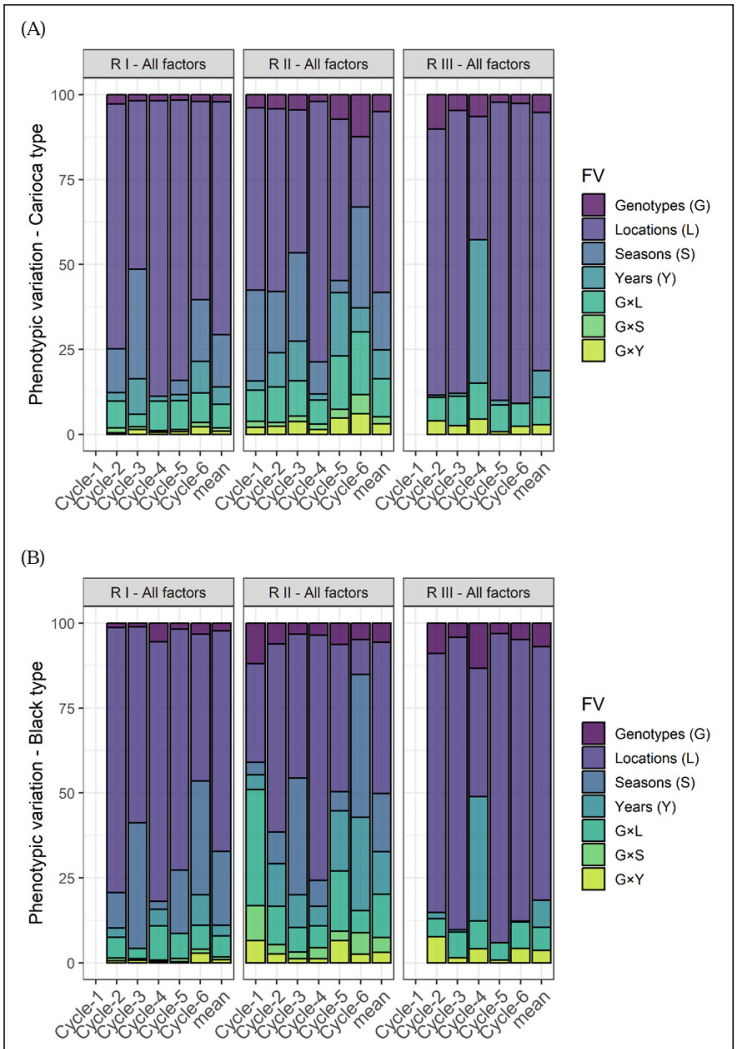

Figure 1 - Decomposition of the total sum of squares of effects from the combined analysis of variance for grain yield (kg ha^{-1}) of the carioca and black commercial group in the three main common bean producing regions of Brazil, across evaluation cycles.

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

environmental factors Location, Season, and Year. In Regions I (RI) and II (RII), analyses were restricted to locations that were common to both sowing seasons and to both years within each cycle. Accordingly, only those locations repeated across both the Season and Year factors were retained, based on genotype yield rankings within each Location × Season × Year combination, whenever feasible.

The correlation estimates for each environmental factor (Location, Season, and Year) interacting with lines was obtained by averaging correlations across all possible combinations of that factor. For RIII, only locations evaluated in both years of the cycle were considered. All analyses were performed using the R software (R CORE TEAM, 2024).

RESULTS

The average yield varied across all cycles for both carioca and black bean groups, with a lower coefficient of variation (Online Resources 1). The combined analysis, considering all cycles and regions for the carioca group, showed significant effects for all sources of variation, except for Season in cycle four (C4), G×S in cycle six (C6) in Region I, and Year in C6 in Region III (Online Resources 2–4). These results indicated the presence of variability among genotypes and differences among Locations, Seasons, and Years. Furthermore, the interaction terms reveal distinct genotype responses to the effects of Location, Season, and Year. For the black bean group, the combined analysis of variance showed significant effects for all sources of variation, except for Year in C3 and C5, and for the Genotype × Year interaction in Region I in C5, as well as for Year in C5 in Region III (Online Resources 5–7).

For the carioca group in Region I, the contribution of the Genotype effect ranged from 0.50% to 2.02%, showing a decreasing trend (Online Resources 2; Figure 1A). This indicated reduced genetic variability, as expected in elite × elite crosses. In all cycles, the Genotype effect was smaller than those of Year, Location, and Season, with an average contribution of 1.17%. The Year effect ranged from 0.73% to 9.02%, being lower than the effects of Location and Season, and accounting for an average of 2.94% of the total variation.

For the significant Season effects, the proportion ranged from 2.02% to 28.13% (Online Resources 2). The variation was high (Figure 1A), particularly in C3, where the contribution reached 28.13%. The mean contribution was 8.80%, second only to the Location effect. The Location factor showed the highest contribution across all cycles, ranging from 14.56% to 52.15%, with an average of 39.24%, approximately four times higher than that of Season. Regarding the average contributions of the G×L, G×S, and G×Y interactions, G×L was the most relevant (Figure 1A), ranging from 2.18% to 5.75%, and representing, on average, about eight times the contribution of G×S and G×Y (Figure 1A).

In Region II, for the carioca group, the Genotype effect ranged from 1.26% to 3.33%, with an average of 2.15% (Online Resources 3). The Year effect varied from 0.93% to 8.63%, being lower than Location and Season effects except in C5, and lower than Genotype effects in two cycles (C1 and C6; Figure 1A). On average, the contribution of the Year effect was 3.67%. In C5, the Season effect was smaller than those of Genotype, Location, and Year, whereas in C6 it was the largest among all, varying from 1.65% to 10.14% (Online Resources 3; Figure 1A). The mean contribution of Season (7.29%) was lower than that of Location. The Location effect showed the greatest contribution in all cycles except C6, ranging from 5.12% to 48.03%, with an average of 22.94%, approximately three times greater than Season and six times greater than Year (Figure 1A). The G×L interaction contributed the most in all cycles, ranging from 3.24% to 7.23%. On average (4.81%), it represented about five times the contribution of G×S and four times that of G×Y. Moreover, only in C4 was the Genotype × Season interaction higher than Genotype × Year (Figure 1A).

In Region III, the Genotype effect ranged from 1.53% to 7.75%, with a decreasing and oscillating pattern across cycles (Online Resources 4; Figure 1A). Its contribution was smaller than that of Location, except for the Year effect in C4. On average, the Genotype effect contributed 3.89%. In the cycles where the Year effect was significant (Online Resources 4), the proportional values ranged from 0.49% to 27.33%, with C4 showing the highest contribution (27.33%) and a mean of 5.91%. This factor was the least important in all cycles (Figure 1A), except in C4 (Online Resources 4; Figure 1A). The average contribution of Location (56.90%) was approximately ten times higher than that of Year and fifteen times higher than that of Genotype. Regarding the mean contributions of the G×L and G×Y interactions, G×L was the most important across all cycles (Online Resources 4; Figure 1A), ranging from 5.28% to 7.37%. The average across cycles (6.07%) showed that G×L was three times greater than G×Y (Figure 1A).

For the black group in Region I, the Genotype effect was of lesser importance, except in

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

C4 (Figure 1B). The proportion of Genotypes ranged from 0.83% to 2.78% across cycles, with an average of 1.49%. Regarding the Year effect, this factor was not significant in two cycles (C3 and C5) (Online Resources 5), and its contribution ranged from 2.44% to 5.34%, averaging 2.01% across cycles. The effects of Season and Location accounted for the largest proportions of total variation (Figure 1B). The contribution of Season ranged from 1.18% to 33.13% (Online Resources 5), with an average of 14.25%, and was highest in cycle C3 (Figure 1B). The Location effect explained 25.45% to 61.63% of the total variation, with an average of 42.37%, which was three times greater than the average contribution of Season (Figure 1B). Still in Region I, the G×L, G×S, and G×Y interactions were similar to those observed in the carioca group. The G×L interaction accounted for an average of 4.07% (2.72% to 5.05%) of the total variation, G×S for 0.48% (0.23% to 0.75%), and G×Y for 0.64% (0.18% to 1.64%) (Online Resources 5). The G×L interaction was approximately six times greater than G×Y and eight times greater than G×S, indicating its dominant influence (Figure 1B). The G×S interaction exceeded G×Y in three (C2, C4, and C5) of the five biennial cycles (Figure 1B).

In Region II, among the main effects, Genotype was the least important (Figure 1B), ranging from 1.34% to 4.11%, with an average of 2.41% (Online Resources 6). Across cycles, the Year effect varied from 1.46% to 11.60%, which was lower than the Location and Season effects, except in C1 and C5, and in C6 for Location (Online Resources 6; Figure 1B), averaging 5.38%. The Season effect ranged from 1.27% to 17.82%. Except in two cycles (C1 and C5), it was the least influential factor, below Genotype, Location, and Year (Figure 1B), and its average contribution was similar to that of the carioca group (Figure 1B). The Location effect showed the largest contribution in all cycles except C6 (Figure 1B), explaining 4.34% to 42.65% of total variation (Online Resources 6). On average (19.02%), this was approximately three times greater than the Season effect and four times greater than the Year effect (Figure 1B). In Region II, the G×L interaction was the most important across all cycles (Figure 1B), representing on average 5.43% of the total variation—approximately five times greater than G×S and four times greater than G×Y—similar in magnitude to the G×L interaction observed in the carioca group (Figure 1B).

For Region III in the black group, the Genotype effect ranged from 2.09% to 9.91%, contributing less than the Location and Year effects (Figure 1B), with an average of 5.08%. For the Year effect, in cycles where it was significant, proportional values ranged from 0.20% to 27.33% (Online Resources 7). The mean value (5.89%) was similar to that of Genotype and lower than that of Location, consistent with the pattern observed in the carioca group (Figure 1B). Location had the largest contribution in all cycles, explaining 28.25% to 70.29% of the total variation (Online Resources 7; Figure 1B). The contribution of Location was nine times greater than that of Year and approximately eleven times greater than that of Genotype (Figure 1B). In the decomposition of genotype–environment interactions, G×L was the most influential in all cycles except C2, ranging from 3.49% to 6.13%. The mean contribution across cycles (5.04%) was approximately twice that of G×Y (Figure 1B). Over the five evaluation cycles, among the main effects, Genotype was the least important, though similar to Year, while Location was the most influential factor. The G×L interaction was evident in both groups and, on average, was 2.9 (carioca) and 1.9 (black) times greater than G×Y (Figure 1B).

Correlation estimates for the carioca group ranged from −0.02 to 0.41 in Region I (Figure 2A), from −0.16 to 0.36 in Region II (Figure 2B), and from −0.10 to 0.38 in Region III (Figure 2C). Only two correlation values were significant: the Season effect in Region I (C2) and Region II (C3). For the black group, correlation estimates ranged from 0.11 to 0.58 in Region I (Figure 2D), from −0.34 to 0.48 in Region II (Figure 2E), and from −0.11 to 0.42 in Region III (Figure 2F). Significance was found for only two values: the Year effect in Region I (C4) and the Location effect in Region II (C6 biennium).

For both groups, carioca (Figure 3A) and black bean (Figure 3B), Selective Accuracy showed high values, with a large number of estimates exceeding 0.70 across the three regions. This indicates high experimental quality and supports the reliability of the data.

DISCUSSION

The most consumed commercial groups of common beans in Brazil are the carioca and black types, accounting for approximately 70% and 20% of the market, respectively (TORRES et al. 2022; EMBRAPA ARROZ E FEIJÃO, 2024). Due to the low use of certified seeds—around 18% in 2021 (ABRASEM, 2025)—the public breeding sector tends to release cultivars with broad adaptation rather than those with specific adaptation, as these are more commercially viable within the bean production chain.

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

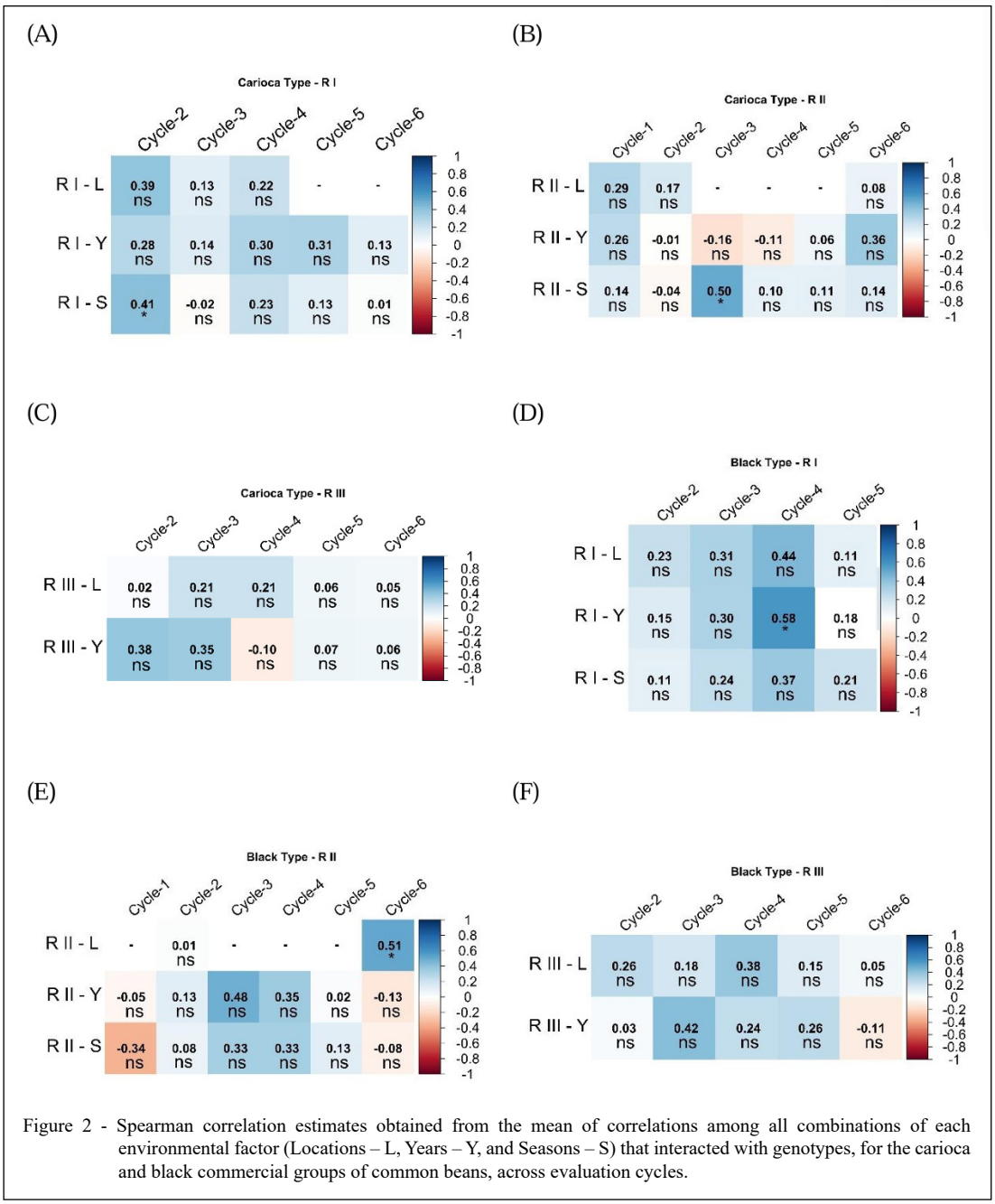

Figure 2 - Spearman correlation estimates obtained from the mean of correlations among all combinations of each environmental factor (Locations – L, Years – Y, and Seasons – S) that interacted with genotypes, for the carioca and black commercial groups of common beans, across evaluation cycles.

In this context, the specific recommendation of cultivars, capitalizing on genotype × environment (G×E) interactions, remains an underused strategy. Understanding the influence of environmental factors through network trials provides valuable information for the recommendation process of breeding lines. This understanding supports the targeted recommendation of genotypes for specific Locations, region, or Sowing Seasons, thereby enhancing the efficiency of genetic potential expression.

Selective accuracy (SA) is an estimate of experimental quality and reflects the reliability of genotypic values. It depends not only on the magnitude of residual variance and the number of replications but also on the ratio between genetic and residual variances associated with the trait

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

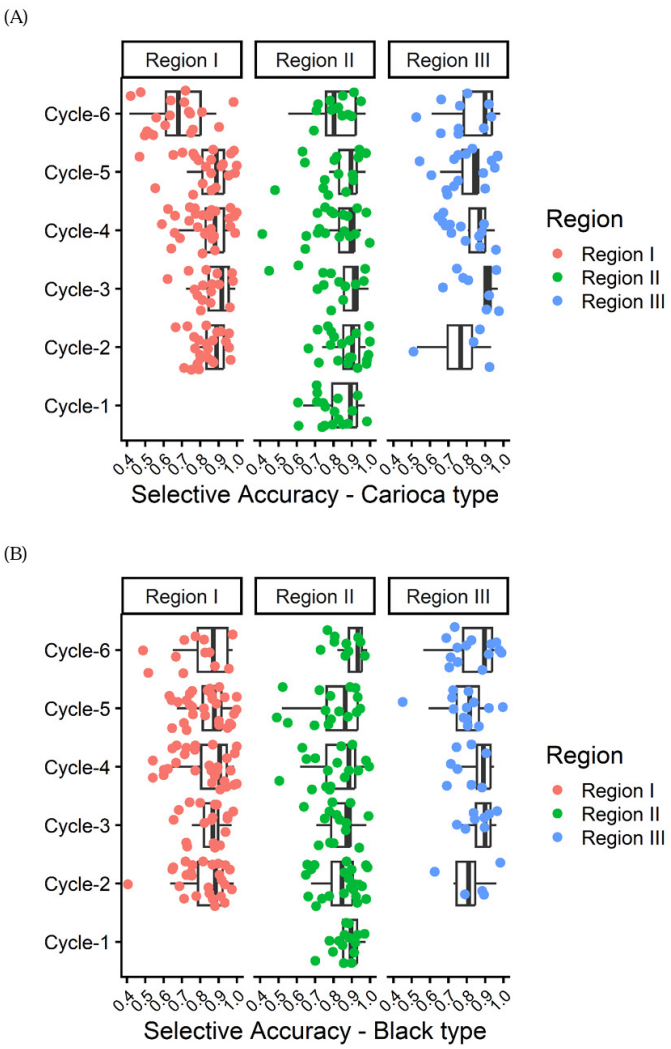

Figure 3 - Distribution of selective accuracy values across the evaluation cycles for the carioca (A) and black (B) commercial groups of common beans.

under evaluation (RESENDE & DUARTE, 2007), as also confirmed by CARGNELLUTTI-FILHO et al. (2009). For both groups, carioca (Figure 3A) and black (Figure 3B), most SA values exceeded 0.70, indicating high precision (RESENDE & DUARTE, 2007; CARGNELLUTTI-FILHO et al. 2009) and the reliability of estimates. The high selective accuracy values support the discrimination of superior genotypes (LIMA et al. 2014).

Significant interaction effects have frequently been reported for the carioca group of common beans in the states corresponding to Region I (PEREIRA et al. 2010b), Region II (PEREIRA et al. 2010c; 2011; 2012), and Region III (PEREIRA et al. 2013). Additionally, MELO et al. (2018) identified the genotype × environment interaction as the second largest source of total variance in the carioca group. The results of the present study confirm the existence of variability among genotypes, differences among environmental factors, and differential genotypic responses to environmental components such as Location, Sowing Season, and Year. Similar inferences were previously reported by TORGA et al. (2013a).

For both grain groups and in all regions, across most evaluation cycles, the Location effect was the most prominent. Likewise, LIMA et al. (2014), analyzing 11 years of VCU (Value for Cultivation and Use) trials in Minas Gerais, found that Location

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

had the greatest influence. Conversely, PEREIRA et al. (2010a; 2011), in Paraná, Santa Catarina, Goiás, and the Distrito Federal, reported that Genotype and Year were more important than Location. RAMALHO et al. (1998) found that Sowing Season (18.89%) and Location (17.19%) were more influential than Year (10,48%) in Minas Gerais. PEREIRA et al. (2011), in Goiás and the Distrito Federal, observed that Year (41.80%) and Sowing Season (8.40%) effects were more important than Location (5.10%). TORGA et al. (2013a) identified Sowing Season (1.30%) as less important than Genotype (8.10%), Location (8.70%), and Year (27.70%) in central Brazil. It is noteworthy that the Year effect often overlaps with that of Location. However, several studies report that the influence of Year is generally smaller than those of Sowing Season and Location (PEREIRA et al. 2010a). For example, CORRÊA et al. (2016), also studying common bean, and TORRES et al. (2022), found a greater contribution of the Year (G×Y) effect. In contrast, the present study demonstrated that Year had a lower influence compared to Sowing Season and Location, since across all evaluation cycles, the Year effect was the least important (Figure 1A and Figure 1B).

The G×L interaction contributed the most across all cycles for both grain groups. These results differ from those obtained by RAMALHO et al. (1998), who worked with carioca beans in Minas Gerais and reported interaction values of G×E (1.91%), G×Y (1.92%), and G×L (1.60%), indicating similar importance among the three factors. However, their study was limited to a few locations, unlike the present research, which evaluated three production regions with different sowing seasons for both carioca and black beans. Similarly, MATOS et al. (2007), in a 30-year study of the common bean breeding program in Minas Gerais, highlighted the evident importance of the G×L interaction. Their findings are consistent with the present study, reinforcing the need to evaluate breeding lines across as many locations as possible to improve the accuracy of estimates—thus, reducing the number of locations is not advisable.

PEREIRA et al. (2011), working with carioca beans in Goiás and the Federal District, found the G×E interaction (3.90%) to be more important than G×Y (2.60%) and G×L (1.90%). However, compared with the present work, their study covered fewer years of evaluation. As reported by FERREIRA et al. (2015), the contribution of the G×Y interaction tends to decrease as the number of years increases. Furthermore, when this interaction is estimated using average data from three cropping seasons within the same year, the variation in R^2 is smaller than when a single season is used. Therefore, in the absence of a significant G×S (Genotype × Sowing Season) interaction, it is necessary to conduct trials in three seasons to obtain more reliable G×Y estimates.

Consistent with the present study, MELO et al. (2022) observed that, in Region III, environmental effects accounted for the largest proportion of total variation, with the genotype × environment interaction being the second most important. Even with only one sowing season, the environmental effect—primarily driven by Locations—remained predominant, which aligns with the quantitative nature of grain yield (Figure 1A and Figure 2B). In studies on common bean in Pernambuco, PEREIRA et al. (2013) reported that among the main effects, Genotype had the least importance (5.90%), while the greatest differences were attributed to Year (25.30%) and Location (34.80%). These findings are in line with the present results, where Location exerted the strongest effect and Genotype the weakest.

SOUZA et al. (2023), studying black beans, also identified the genotype × environment interaction as the second most important component of total variation in Region II. However, the authors did not decompose the environmental factors. Understanding the magnitude of the effects of Location, Sowing Season, and Year is essential for optimizing the design of VCU trial networks. In this study, among the environmental interactions, the G×L effect was the most important in all cycles for both grain groups (Figure 1A and Figure 1B). TORGA et al. (2013a), studying black beans in Central Brazil, found the G×S interaction (4.20%) to be more important than G×Y (4.10%) and G×L (3.00%). In contrast, the importance of G×L was evident in both groups here, being on average 2.9 (carioca) and 1.9 (black) times greater than G×Y (Figure 1A and Figure 1B). PEREIRA et al. (2013) reported similar findings, with G×L being 3.6 times more important than G×Y in Pernambuco, and PEREIRA et al. (2010b) also found G×L to be 1.7 times more important than G×Y. Conversely, PEREIRA et al. (2011) and TORGA et al. (2013b) found the opposite trend, with G×Y being 1.4 times more important than G×L. However, those studies were based on fewer years and locations. Therefore, the results obtained in the present study—supported by a larger dataset spanning multiple trials and years—provide more reliable estimates, confirming the greater importance of the G×L interaction compared to G×Y.

The absence of significance and the low correlation values further confirm the existence of genotype interactions with different environmental factors. The lack of consistency in yield means across environmental factors highlights the need for specific genotype recommendations and regularly distributed

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

trials across regions, sowing seasons, and years. The absence of correlation underscores the importance of maintaining multi-location and multi-season trials to capture environmental effects and interactions, thus improving the informativeness of the dataset (Figure 2).

In Embrapa's common bean breeding program, cultivar recommendations are based on the performance of breeding lines across the main production regions. It is evident that conducting trials over multiple seasons and years results in different levels of information, as specific interactions (Location, Sowing Season, and Year) contribute with varying magnitudes to total phenotypic variation. Across the three regions and for both carioca and black bean groups, the Location effect was the most pronounced (Figure 1A and Figure 1B), emphasizing the need for evaluations in a greater number of environments. Although sowing seasons differ across regions, the combined interactions among Genotypes, Locations, Seasons, and Years were not predominant (Figure 1A and Figure 1B), suggesting that the number of trials per season could be reduced, focusing on the most relevant ones for each region. Furthermore, given the low magnitude of the Year effect, maintaining only a minimum number of years of trials is sufficient for cultivar release.

CONCLUSION

Genotype × environment interactions and the influence of environmental factors were observed in all cultivar recommendation regions in Brazil, including the Center-South (RI), Central (RII) and Northeast (RIII) regions. The Location effect and its interaction with Genotype were the most important sources of variation across the three recommendation regions for both carioca and black bean groups. Evaluations across multiple Locations should be prioritized over Sowing Seasons and Years to ensure more efficient and reliable recommendations of new cultivars for Brazil's main bean-producing regions.

SUPPLEMENTARY MATERIAL

The supplementary material is available from the corresponding author upon reasonable request or through the following link: <https://drive.google.com/file/d/1zkeB_1nKX6BUWwnlbzDP_LhVCwliFSaT/view?usp=sharing>.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA).

ACKNOWLEDGMENTS

The authors are grateful to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the grants to Leonardo Cunha Melo, Helton Santos Pereira and Patrícia Guimarães Santos Melo. We thank the entire common bean breeding staff at Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), especially the research assistants and field workers.This study wasfinanced in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brasil - Finance code 001.

DECLARATIONS OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the study conception and manuscript preparation, critically reviewed the content and approved the final version.

BIOETHICS AND BIOSECURITY COMMITTEE APPROVAL

The study followed national/institutional guidelines during the research. All permissions and licenses were obtained in both public and private contexts. All sampling conducted on public and private lands adhered to the permissions. All directives were conducted with consideration for evaluation in final trials breeding programs.

DECLARATION OF USE OF ARTIFICIAL INTELIGENCE

No artificial intelligence tools were used in the preparation of this article.

REFERENCES

ABRASEM. **Associação Brasileira de Sementes e Mudas**. 2025. Available from: <https://www.abrasem.com.br/estatisticas/>. Accessed: Sept. 24, 2025.

AMBRÓSIO, M. et al. Adaptability and stability of black bean genotypes with normal and early cycle. **Euphytica**, v.220, n.2, p.1-12, 2024. Available from: <https://doi.org/10.1007/s10681-023-03282-2>. Accessed: Oct. 27, 2025. doi: 10.1007/s10681-023-03282-2.

BALDIN, R. C. et al. Yield stability of common bean genotypes in the state of Santa Catarina, Brazil. **Pesquisa Agropecuaria Brasileira**, v.56, e02302, 2021. Available from: <https://doi.org/10.1590/S1678-3921.pab2021.v56.02302>. Accessed: Aug. 28, 2025. doi: 10.1590/S1678-3921.pab2021.v56.02302.

BRASIL. Instrução Normativa nº 25, de 23 de maio de 2006. Requisitos mínimos para a determinação do valor de cultivo e uso – VCU de feijão (*Phaseolus vulgaris*) para inscrição no registro nacional de cultivares – RNC. **Diário Oficial da República Federativa do Brasil**,Brasília. 2026. Available from: <https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/sementes-e-mudas/publicacoes-sementes-e-mudas/INN25de23demaiode2006.pdf>. Accessed: Mar. 27, 2024.

SciELO Preprints - This document is a preprint and its current status is available at: https://doi.org/10.1590/0103-8478cr20260049

CARGNELUTTI-FILHO, A. et al. Measures of experimental precision in common bean and soybean genotype trials. **Pesquisa Agropecuária Brasileira**, v.44, n.10, p.1225-1231, 2009. Available from: <https://doi.org/10.1590/S0100-204X2009001000003>. Accessed: Nov. 04, 2025. doi: 10.1590/S0100-204X2009001000003.

CORRÊA, A. M. et al. Selection of common bean genotypes for the cerrado/pantanal ecotone via mixed models and multivariate analysis. **Genetics and Molecular Research**, v.15, n.4, p.1-9, 2016. Available from: <http://dx.doi.org/10.4238/gmr15048888>. Accessed: Dec. 10, 2025. doi: 10.4238/gmr15048888.

DUARTE, J. B.; VENCOVSKY, R. **Interação genótipos x ambientes**: uma introdução à análise "AMMI". Sociedade Brasileira de Genética, Ribeirão Preto, 1999. Available from: <https://www.researchgate.net/publication/235941257_Interacao_genotipos_x_ambientes_uma_introducao_a_analise_AMMI>. Accessed: Jan. 03, 2025.

EMBRAPA ARROZ E FEIJÃO. **Dados de conjuntura da produção de feijão (*Phaseolusvulgaris* L.) e caupi (*Vigna unguiculata* L. Walp) no Brasil: 1985–2022**. 2024. Available from: <https://www.cnpaf.embrapa.br/socioeconomia/index.htm>. Accessed: Aug. 06, 2024.

FERREIRA, R. A. D. C. et al. Implications of the number of years assessment on recommendation of common bean cultivars. **Plant Breeding**, v.134, n.5, p.599-604, 2015. Available from: <https://doi.org/10.1111/pbr.12302>. Accessed: Feb. 10, 2025. doi: 10.1111/pbr.12302.

LIMA, L. K. et al. Implications of predictable and unpredictable environmental factors in common bean VCU trials in Minas Gerais. **Crop Breeding and Applied Biotechnology**, v.14, n.3, p.146-153, 2014. Available from: <https://doi.org/10.1590/1984-70332014v14n3a22>. Accessed: Dec. 15, 2024. doi: 10.1590/1984-70332014v14n3a22.

MATOS, J. W. et al. Thirty two years of common bean breeding in Minas Gerais state. **Ciência e Agrotecnologia**, v.31, n.6, p.1749-1754, 2007. Available from: <https://www.scielo.br/j/cagro/a/65qb9KCYcPmqhJ6DKN5BSFS/?format=pdf&lang=pt&ilang=pt_BR>. Accessed: Dec. 20, 2024.

MELO, G. G. et al. Adaptability and stability of carioca bean pre-cultivars in Agreste-Sertão Pernambucano. **Revista Brasileira de Ciências Agrárias**, v.17, n.3, p.e1697-e1697, 2022. Available from: <https://doi.org/10.5039/agraria.v17i3a1697>. Accessed: Jan. 28, 2026. doi: 10.5039/agraria.v17i3a1697.

MELO, P. G. S. et al. Adaptability and stability of common bean genotypes in family farming systems. **Pesquisa Agropecuária Brasileira**, v.53, n.2, p.189–196, 2018. Available from: <https://doi.org/10.1590/S0100-204X2018000200007>. Accessed: Nov. 12, 2024. doi: 10.1590/S0100-204X2018000200007.

PEREIRA, H. S. et al. Environmental influence in common bean cultivars grown in Brazilian savannah with low altitude. **Bragantia**, v.71, n.2, p.165-172, 2012. Available from: <https://doi.org/10.1590/S0006-87052012005000024>. Accessed: Nov. 01, 2025. doi: 10.1590/S0006-87052012005000024.

PEREIRA, H. S. et al. Genetic, environmental and genotype × environment interaction effects on the common bean grain yield and commercial quality. **Semina: Ciências Agrárias**, v.38, n.3, p.1241-1250, 2017. Available from: <https://doi.org/10.5433/1679-0359.2017v38n3p1241>. Accessed: Oct. 17, 2024. doi: 10.5433/1679-0359.2017v38n3p1241.

PEREIRA, H. S. et al. Interaction between common bean genotypes and environments in Pernambuco State: stability, environmental stratification and decomposition of interaction **Semina: Ciências Agrárias**, v.34, n.6, p.2603-2614, 2013. Available from: <https://doi.org/10.5433/1679-0359.2013v34n6p2603>. Accessed: Sept. 09, 2024. doi: 10.5433/1679-0359.2013v34n6p2603.

PEREIRA, H. S. et al. Complex interaction between genotypes and growing seasons of carioca common bean in Goiás/Distrito Federal. **Crop Breeding and Applied Biotechnology**, v.11, n.3, p.207-215, 2011. Available from:<https://doi.org/10.1590/S1984-70332011000300002>. Accessed: Jun. 25, 2024. doi: 10.1590/S1984-70332011000300002.

PEREIRA, H. S. et al. **Regionalização de áreas produtoras de feijão comum para recomendação de cultivares no Brasil**. Embrapa Arroz e Feijão, Santo Antônio de Goiás, 2010a. Available from: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/857164>. Accessed: Apr. 19, 2024.

PEREIRA, H. S. et al. Indication of common bean cultivars based in joint evaluation of different growing seasons. **Pesquisa Agropecuária Brasileira**, v.45, n.6, p.571-578, 2010b.Availablefrom:<https://www.scielo.br/j/pab/a/ 3tLmF6f8Cb LCQXRFM QVV6T v/?format=pdf&lang= pt&ilang=pt_BR>. Accessed: May, 19, 2024.

R CORE TEAM. **R: A Language and Environment for Statistical Computing**. R Foundation for Statistical Computing, Vienna, Austria, 2024. Available from: <https://www.R-project.org/>. Accessed: Dec. 12, 2024.

RAMALHO, M. A. P. et al. Interactions of genotypes x sowing dates, years x and places on common bean cultivars evalution in the south and "Alto Paranaiba" regions of Minas Gerais State. **Ciência e Agrotecnologia**, v.22, n.2, p.176-181, 1998. Available from: <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1017707/1/ca19980001.pdf>. Accessed: Mar. 22, 2024.

RESENDE, M. D. V and DUARTE, J. B. Precision and quality control in variety trials. **Pesquisa Agropecuária Tropical**, v.37, n.3, p.182-194, 2007. Available from: <https://revistas.ufg.br/pat/article/view/1867/1773>. Accessed: Jul. 17, 2024.

SOUZA, A. G. et al. Adaptability and stability of black bean genotypes for Rio de Janeiro, by GGE biplot analysis. **Crop Breeding and Applied Biotechnology**, v.23, n.2, e43972323, 2023. Available from: <http://dx.doi.org/10.1590/198470332023v23n2a15>. Accessed: Jun. 23, 2025. doi: 10.1590/198470332023v23n2a15.

TORGA, P. P. et al. Interaction of common beans cultivars of the black group with years, locations and sowing seasons. **Euphytica**, v.189, n.2, p.239-248, 2013a. Available from: <https://link.springer.com/article/10.1007/s10681-012-0793-y>. Accessed: May,14, 2025. doi: 10.1007/s10681-012-0793-y.

TORGA, P. P. et al. Decomposition of the interaction of common black bean group genotypes with the environment. **Agricultural Sciences**, v.4, n.12, p.683-688, 2013b. Available from: <https://content.scirp.org/pdf/as_2013122314481195.pdf>. Accessed: Nov. 08, 2025. doi: 10.4236/as.2013.412092.

TORRES, M. H. R. M. et al. Genetic parameters and selection of black bean lines for resistance to fusarium wilt and yield. **Pesquisa Agropecuaria Brasileira**, v.57, e02846, 2022. Available from: <https://doi.org/10.1590/S1678-3921.pab2022.v57.02846>. Accessed: Dec. 19, 2025.doi: 10.1590/S1678-3921.pab2022.v57.02846.

This preprint was submitted under the following conditions:

- The authors declare that the necessary Terms of Free and Informed Consent of participants or patients in the research were obtained and are described in the manuscript, when applicable.
- The authors declare that the preparation of the manuscript followed the ethical norms of scientific communication.
- The authors declare that they are aware that they are solely responsible for the content of the preprint and that the deposit in SciELO Preprints does not mean any commitment on the part of SciELO, except its preservation and dissemination.
- The authors declare that the data, applications, and other content underlying the manuscript are referenced.
- The deposited manuscript is in PDF format.
- The authors declare that the research that originated the manuscript followed good ethical practices and that the necessary approvals from research ethics committees, when applicable, are described in the manuscript.
- The authors declare that once a manuscript is posted on the SciELO Preprints server, it can only be taken down on request to the SciELO Preprints server Editorial Secretariat, who will post a retraction notice in its place.
- The authors agree that the approved manuscript will be made available under a Creative Commons CC-BY license.
- The submitting author declares that the contributions of all authors and conflict of interest statement are included explicitly and in specific sections of the manuscript.
- The authors declare that the manuscript was not deposited and/or previously made available on another preprint server or published by a journal.
- If the manuscript is being reviewed or being prepared for publishing but not yet published by a journal, the authors declare that they have received authorization from the journal to make this deposit.
- The submitting author declares that all authors of the manuscript agree with the submission to SciELO Preprints.