Genetics/ Original Article

Simultaneous selection for yield, adaptability, and genotypic stability in immature cowpea using REML/BLUP

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Abstract – The objective of this work was to select cowpea genotypes simultaneously for high yield of immature grains, adaptability, and genotypic stability, taking into account genotype x environment interactions. The mixed models restricted maximum likelihood (REML)/best linear unbiased prediction (BLUP) were used. Sixteen cowpea genotypes were evaluated in nine environments, consisting of a combination of location (Pentecoste in the state of Ceará, Acaraú in Ceará, Teresina in Piauí, and Mossoró in Rio Grande do Norte, Brazil) and year (2012, 2013, 2014, 2015, and 2017). In all trials, a randomized complete block design with four replicates was used. Significant differences were observed for effects of genotypes and the genotype x environment interaction. Environmental variance was the largest component of phenotypic variance, followed by the genotype x environment interaction and genotypic variances. The immature grain yield of the evaluated cowpea genotypes interacts strongly with the studied environments, resulting in a low genotypic correlation between environments. The MNC00-595F-27, MNC05-847B-123, and BRS Tumucumaque cowpea genotypes present high yield of immature grains, adaptability, and genotypic stability, being the most suitable for cultivation in the states of Ceará, Piauí, and Rio Grande do Norte or in other environments with similar soil and climatic conditions.

Index terms: *Vigna unguiculata*, genotype x environment interaction, immature cowpea.

Seleção simultânea para produtividade, adaptabilidade e estabilidade genotípica em feijão-caupi imaturo via REML/BLUP

Resumo – O objetivo deste trabalho foi selecionar genótipos de feijão-caupi simultaneamente para alta produção de grãos imaturos, adaptabilidade e estabilidade genotípica, ao se considerar interações genótipos x ambientes. Foram utilizados os modelos mistos máxima verossimilhança restrita (REML)/ melhor predição linear não viciada (BLUP). Avaliaram-se 16 genótipos de feijão-caupi em nove ambientes, que consistiram de combinação de local (Pentecoste no Ceará, Acaraú no Ceará, Teresina no Piauí e Mossoró no Rio Grande do Norte) e ano (2012, 2013, 2014, 2015 e 2017). Em todos os ensaios, utilizou-se o delineamento de blocos ao acaso com quatro repetições. Foram observadas diferenças significativas para os efeitos de genótipos e interação genótipo x ambiente. A variância ambiental foi o maior componente da variância fenotípica, seguido das variâncias da interação genótipo x ambiente e genotípica. A produtividade de grãos imaturos dos genótipos de feijão-caupi avaliados interage fortemente com os ambientes estudados, o que resulta em

baixa correlação genotípica entre os ambientes. Os genótipos de feijão-caupi MNC00-595F-27, MNC05-847B-123 e BRS Tumucumaque apresentam alta produtividade de grãos imaturos, adaptabilidade e estabilidade genotípica, sendo os mais recomendáveis para cultivo nos estados do Ceará, Piauí e Rio Grande do Norte ou em outros ambientes com condições climáticas e de solo similares.

Termos para indexação: *Vigna unguiculata*, interação genótipo x ambiente, feijão-verde.

Introduction

Cowpea [*Vigna unguiculata* (L.) Walp.], known in Brazil as "feijão-caupi", "feijão-macassar" or "feijão-de-corda", is a species with a broad genetic variability, efficient adaptation, high productive capacity, and excellent nutritional value. Due to its versatility, it is used for several purposes and in different production systems (Freire Filho, 2011).

In Brazil, the three main market segments for cowpea are dry beans, green beans (pods to obtain the immature grain or the immature grain already threshed), and seeds. Other segments include: bean pods (yardlong bean) of the Sesquipedalis cultivation group, which are currently more concentrated in some states of the Northern region, but with great possibilities of expansion; and industrially processed beans, in an initial phase, but with good prospects (Freire Filho et al., 2017).

The production of cowpea is mainly focused on the consumption of dry grains. However, the market for immature grains is growing every day, mainly in the Northeastern region of Brazil, where it is highly appreciated, being used as the main component of several typical dishes, especially "baião-de-dois", a flavorful combination of rice and beans (Rocha et al., 2012).

The market for immature cowpea is highly promising, as it represents an important source of employment and income around the producing region (Freire Filho, 2011; Rocha et al., 2017a). However, it is currently characterized by the inexistence of improved cultivars and by the cultivation of landraces, generally with a low grain yield, late maturation cycle, and low disease resistance (Sousa et al., 2015). In addition, the pod is usually harvested at a stage with about 60 to 70% moisture (Sousa et al., 2015).

Although there are no official statistics on the area or on the cultivation of cowpea for the production of immature pods and grains in Brazil, both are quite significant for the agribusiness of the crop. The reason is that immature cowpea grains are traditionally grown and consumed in practically all states of the Northeastern region of the country.

However, the traditional cultivars used do not present completely favorable characteristics for cultivation and commerce, representing losses for the producers. Therefore, there is a great demand for more productive and better post-harvest cowpea cultivars, requiring the selection and development of materials with these specific characteristics according to Souza et al. (2019); this will add more value to the product and contribute to a greater sustainability of the cowpea agribusiness for immature pods and grains in Brazil.

In the breeding process, which includes the selection and recommendation of cultivars for a particular region, it is necessary to evaluate how genotypes behave in several environments due to environmental variations or to the genotype x environment (GxE) interaction. These variations affect the performance of genotypes in different environments, and the best strategy to manage the GxE interaction is to select genotypes with high adaptability and stability (Rocha et al., 2012).

The procedure based on mixed models has been applied in different research lines in the plant breeding area, such as in the analysis of the GxE interaction. It allows the estimation of the components of variance by the restricted maximum likelihood (REML) and of the genotypic value by the best linear unbiased prediction (BLUP), being called REML/BLUP. One of the advantages of this approach is that it allows simultaneous genotypic selection for yield, adaptability, and stability in the context of mixed models, through the use of the harmonic mean of the relative performance of genotypic values (HMRPGV) (Resende, 2007).

The REML/BLUP procedure has been widely used in studies of the adaptability and stability of dry grain yield in cowpea (Torres et al., 2015, 2016; Santos et al., 2016; Carvalho et al., 2017; Torres Filho et al., 2017; Rocha et al., 2017b, 2017c). However, works using this approach to assess the adaptability and stability of immature grain yield are still rare (Torres Filho et al., 2017).

The objective of this work was to select cowpea genotypes simultaneously for high yield of immature grains, adaptability, and genotypic stability, taking into account genotype x environment interactions.

Materials and Methods

For the experiment, the following 16 cowpea genotypes (lines and cultivars) were used, listed after their commercial subclasses: "Verde", MNC00-586F-303-9, MNC00-595F-2, MNC00-595F-27, MNC05-835B-15, MNC05-835B-16, MNC05-841B-49, MNC05-847B-123, and MNC05-847B-126; "Branco liso", MNC99-541F-15, BRS Guariba, BRS Tumucumaque, BRS Xiquexique, and Vagem Roxa-THE; "Canapu", Paulistinha; "Azulão", Azulão-MS; and "Sempre verde", Sempre Verde-CE. The genotypes were obtained from the cowpea germplasm bank and breeding program of Embrapa Meio-Norte, located in Teresina, in the state of Piauí, Brazil. Since Azulão-MS, Sempre Verde-CE, and Vagem Roxa-THE are landraces commercialized in the market of immature cowpea pods and grains, they were used as controls.

The trials were conducted in Brazil, in different municipalities and years: Teresina (05º05'S, 42º48'W, at 72 m altitude) in 2012, 2013, and 2017, in the state of Piauí; Acaraú (2º53'S, 40º6'W, at 24 m altitude) in 2013 and 2015, and Pentecoste (3º47'S, 39º16'W, at 45 m altitude) in 2013, in the state of Ceará; and Mossoró (5º11'S, 37º20'W, at 18 m altitude) in 2014 (two seasons) and 2015, in the state of Rio Grande do Norte. The climate of all environments is tropical with a dry winter, according to the Köppen-Geiger classification (Alvares et al., 2013). All trials were carried out under irrigation condition, except the one in Acaraú, in the state of Ceará, in 2015, which was conducted under rainfed condition. In the trials performed with irrigation, a conventional sprinkler was used, with a medium water depth of 20 mm over 2 hours and a watering shift of five days. The evaluated environments consisted of a combination of location and year, resulting in nine environments: Pentecoste in 2013, Acaraú in 2013, Acaraú in 2015, Teresina in 2012, Teresina in 2013, Teresina in 2017, Mossoró in 2014 – first season (between March and May), Mossoró in 2014 – second season (between August and October), and Mossoró in 2015. These sites were selected due to their availability, as well as to the ease of conducting the trials (infrastructure), the tradition of consumption and trade, and the interest of farmers there.

A randomized block design was used, with four replicates. The experimental plot had the dimensions of 2.0x5.0 m and consisted of four rows; the two central rows were considered as the useful area. The spacing between rows was 0.50 m and between holes within the row, 0.25 m, resulting in 20 holes per row. Four seeds were sown per hole, and, 15 days after sowing, thinning was performed, maintaining two plants per hole, totalizing 160 plants in the plot and 80 plants per useful area of the plot.

Crop management was carried out whenever necessary to ensure that there was no competition between cowpea plants and weeds and that the crop was not over attacked by pests and diseases. Immature cowpea grains were harvested and threshed manually. The immature grain yield of the plot area was measured in grams per useful plot area, extrapolated to kilograms per hectare.

The yield data of the immature grains obtained in the different environments were subjected to the statistical analysis. Statistical model 54 (stability, adaptability, and yield: blocks, genotypes, several environments, and one observation per plot) of the Selegen-REML/BLUP software was used (Resende, 2007). The following model was adopted: y = Xb + Zg + Wc + e, where y, b, g, c, and e correspond, respectively, to the vectors of observed values, fixed effects of blocks within different environments, random effects of genotypes, random effects of the GxE interaction, and random errors; and X, Z, and W correspond, respectively, to the incidence matrices for b, g, and c.

The following parameters were estimated: phenotypic variance (σ_f^2); genotypic variance (σ_g^2); residual variance (σ_e^2); variance of the genotype x environment interaction (σ_{ge}^2); genotypic correlation ($r_{gloc} = \sigma_{ge}^2 / \sigma_g^2 + \sigma_{ge}^2$); heritability of the average of genotypes $h_{mg}^2 = \sigma_g^2 / (\sigma_g^2 + \sigma_e^2 / e)$, where e is the number of environments; accuracy in the selection of genotypes ($\hat{r}_{gg} = \sqrt{h_{mg}^2}$); and relative coefficient of variation, obtained by CV_g/CV_e, where CV_g and CV_e are the coefficients of genetic and environmental variations, respectively.

The significance of the effects of the model was estimated by the deviance analysis (Resende, 2002). The deviances were obtained through analyzes with and without the effects of g, b, and ge. The deviation without these effects was then subtracted from each complete model deviation and compared with the chi-square value, with 1 degree of freedom, at 1% probability.

Based on the used model, the empirical BLUP predictors (eBLUP or REML/BLUP) of the genotypic values free

of the GxE interaction were given by $\hat{\mu} + \hat{g}_i$, where μ is the average of all environments and $\hat{g}_i$ is the genotypic effect free of the GxE interaction. For each environment j, genotypic values (GV$_{ij}$) were predicted by $\hat{\mu}_j + \hat{g}_i + (g\hat{e})_{ij}$, where μ_j is the average of environment j, $\hat{g}_i$ is the genotypic effect of genotype i in environment j, and $(g\hat{e})_{ij}$ is the effect of the G×E interaction relative to genotype i. The prediction of genotypic values by capitalizing on the average GxE interaction (ge$_a$) in the different environments was given by $\hat{\mu}_j + \hat{g}_i + g\hat{e}_a$, being calculated by $\hat{\mu} + \left\lfloor \left(\hat{\sigma}_g^2 + \hat{\sigma}_e^2 / e\right) \middle/ \hat{\sigma}_g^2 \right\rfloor \hat{g}_i$, where μ is the general average of all environments, e is the number of environments, and $\hat{g}_i$ is the genotypic effect of i (Resende, 2007).

The harmonic mean of genotypic values (HMGV) was obtained by the equation:

$$HMGV_i = e \middle/ \sum_{j=1}^{e} \left(1/GV_{ij}\right),$$

where e is the number of environments in which genotype i was evaluated; and GV$_{ij}$ is the genotypic value of genotype i in environment j, expressed as the proportion of the mean of that environment (Resende, 2007). The relative performance of genotypic values (RPGV) was obtained according to the expression:

$$RPGV_i = \left(1/e\right) \sum_{j=1}^{e} \left(GV_{ij}/\mu_j\right),$$

where μ_j is the mean of environment j. The joint selection considering, simultaneously, genotype yield, stability, and adaptability was given by the HMRPGV, calculated according to the equation:

$$HMRPGV_i = e \middle/ \sum_{j=1}^{e} \left(1/RPGV_{ij}\right),$$

whose terms have already been explained.

The lower the standard deviation of the behavior of the genotypes in the environments, the higher the HMGV; therefore, selection by higher HMGV implies selection for yield and stability, simultaneously. The mean genotypic value, capitalizing on adaptability, is obtained by the relative performance of genotypic values multiplied by the general mean of all environments (RPGVμ). The average genotypic value penalized by instability and capitalized by stability is determined by the HMRPGV multiplied by the general average of all environments (HMRPGVμ) (Resende, 2007).

Results and Discussion

Genotypes and the GxE interaction were significant (p≤0.01) by the deviance analysis (Table 1), indicating the presence of genetic variability for immature grain yield in the group of evaluated genotypes, as well as of a differentiated behavior of genotypes in the different environments. The existence of the GxE interaction causes an inconsistency in yield, meaning that one genotype may stand out in a given environment and another may not, which makes it necessary to evaluate the adaptability and stability of different genotypes. According to Rocha et al. (2012), the identification and selection of genotypes that are highly productive and stable in various environments is one of the main objectives of cowpea breeding programs. Aquino et al. (2016) evaluated the adaptability and stability of the immature grain yield of 30 cowpea genotypes in the region of Juazeiro, in state of Bahia, and in the municipality of Petrolina, in the state of Pernambuco, both in Brazil, and also found significant differences for the genotype and GxE interaction effects.

According to the components of variance by the REML, environmental variance contributed the most (51%) to phenotypic variance, followed by the GxE interaction variance (36%), and genotypic variance (13%) (Table 2). The high influence of environmental variance can be justified by the polygenic nature of the trait in question. In other studies evaluating the dry grain yield of cowpea genotypes in multiple environments (Torres et al., 2015; Rocha et al., 2017b, 2017c), a higher proportion of environmental variance was also observed when the genotypic and G×E interaction variances were taken into account.

In spite of a higher effect of environmental factors, shown by the relative coefficient of variation of 0.49,

Table 1. Deviance analysis for the immature grain yield of 16 cowpea (*Vigna unguiculata*) genotypes evaluated in nine environments, consisting of a combination of locations in the states of Ceará, Piauí, and Rio Grande do Norte, Brazil, and of years from 2012 to 2017.

Effect	Deviance[1]	LRT (chi-square)[2]
Genotype	7,337.03	12.84**
Genotype x environment interaction	7,425.17	100.98**
Residual	-	-
Complete model	7,324.19	-

[1]Deviance of the adjusted model without the cited effects, with a distribution for 1 degree of freedom. [2]LRT, likelihood ratio test. **Chi-square at 1% probability.

the mean genotype heritability among the various environments had a high magnitude of 0.70 (Table 2), indicating a favorable situation for selection. The heritability obtained in the present study was similar to that found by Torres et al. (2015), who evaluated the dry grain yield of 20 cowpea genotypes in several environments of the state of Mato Grosso do Sul, Brazil, but was higher than that reported by Torres Filho et al. (2017), who observed a low magnitude of 0.4 for the immature grain yield of cowpea genotypes in the climate and soil conditions of Mossoró, in the state of Rio Grande do Norte.

According to Chiorato et al. (2008), average heritability is based on the number of replicates and plants assessed per plot in the experiment. The size of the experimental area of the present study may have contributed positively to the reduction of environmental effects, because the genotypes were represented by 80 plants in the useful area of the plot used for the evaluations.

Selective accuracy is an important parameter in the context of genotype evaluation and corresponds to the correlation between the true genotypic value of each genotype, which is estimated or predicted from experimental data, varying from 0 to 1; the appropriate accuracy values are those close to unity (Resende & Duarte, 2007). The accuracy of 0.83 obtained in the present study was considered high (Table 2), indicating

Table 2. Estimates of the components of variance by the individual restricted maximum likelihood and genetic parameters for 16 cowpea (*Vigna unguiculata*) genotypes in nine environments, consisting of a combination of locations in states of Ceará, Piauí, and Rio Grande do Norte, Brazil, and of years from 2012 to 2017.

Genetic parameter	Estimative
Genotypic variance	40,316.28
Residual variance	164,265.09
Genotype x environment interaction variance	116,423.13
Phenotypic variance	321,004.50
Heritability of the average of genotypes	0.70
Selective accuracy	0.83
Genotypic correlation among environments	0.26
Relative coefficient of variation (CV_g/CV_e)[1]	0.49

[1]CV_g, coefficient of genetic variation; and CV_e, coefficient of environmental variation.

experimental quality, as well as safety and reliability in the selection of superior genotypes for immature grain yield. This estimate was higher than that found by Torres Filho et al. (2017), who observed a low precision of 0.20 while also evaluating the immature grain yield of cowpea genotypes under the edaphoclimatic conditions of Mossoró, in the state of Rio Grande do Norte.

The second component that most influenced phenotypic variance was the GxE interaction variance, which resulted in a low genotype correlation of 0.26 among environments (Table 2). These results show that the GxE interaction is probably of the complex type, causing a significant inversion in genotype classification throughout environments (Resende, 2007). This could lead to difficulties in the selection of genotypes with a broader adaptation, showing the importance of analyzing adaptability and stability in order to provide more accurate information for the selection of cowpea genotypes with more predictable immature grain yield.

Rocha et al. (2017b, 2017c) evaluated the dry grain yield of 20 cowpea genotypes in the Northeastern region of Brazil and also found that the GxE interaction was the second component to influence phenotypic variance. However, Torres et al. (2016) reported similar percentages for the GxE interaction and the environmental variances, when studying cowpea genotypes in environments in the state of Mato Grosso do Sul.

The average immature grain yield was 1,599 kg ha^{-1} (Table 3), which was considered low, probably because most of the trials were conducted under irrigation and there was overgrowth during the production period in some of them. This average was lower than those of 1,957 and 2,390 kg ha^{-1} found by Sousa et al. (2015) for rainfed and irrigated cultivation, respectively, when evaluating 16 cowpea genotypes in the municipality of Teresina, in the state of Piauí, Brazil, and than that of 2,827 kg ha^{-1} reported by Freitas et al. (2016) for irrigated cultivation, when studying 12 cowpea genotypes under the soil and climate conditions of the municipality of Mossoró, in the state of Rio Grande do Norte. However, the average immature grain yield obtained in the present study was superior to that of 1,353 kg ha^{-1} observed by Silva et al. (2013) for rainfed cultivation, when evaluating 8 cowpea cultivars under the edaphoclimatic conditions of the municipality of Serra Talhada, in the state of Pernambuco, Brazil.

According to the estimates of mean components by the BLUP and to the confidence intervals associated with genotypic values (μ + g), BRS Tumucumaque, MNC00-595F-27, and MNC05-847B-123 showed higher values than most of the evaluated genotypes, as well the highest genetic gains of 292.58 kg or 18.29%, 288.52 kg or 18.04%, and 248.35 kg or 15.53%, respectively, compared with the general average (Table 3). The gains obtained in the present study were higher than those observed by Rocha et al. (2017c), who assessed the dry grain yield of 20 cowpea genotypes in the Northeastern region of Brazil and obtained a gain of 10.56, 8.52, and 7.76% for the three best genotypes.

The five best genotypes based on the HMGV and RPGV criteria (Table 4) do not necessarily correspond to the five best by the criterion of the average genotypic value (μ + g). The coincidence was 80% for both HMGV and RPGV, with a reverse order among the matched genotypes. The coincidence among the five best genotypes by the mean genotypic value and HMRPGV was 100%; however, there was also an inversion in genotype order. This shows that it is possible to make reliable predictions about genetic values with a single selection criterion, covering yield, stability and adaptability, which allows a more refined selection.

These results differed from those of Torres et al. (2016), who reported a coincidence in the order of the five best genotypes of approximately 80%, considering the mean genotypic values by the HMGV and HMRPGV, and of 40% by the RPGV, while evaluating the dry grain yield of 20 cowpea genotypes in the state of Mato Grosso do Sul, Brazil. Rocha et al. (2017b) assessed the dry grain yield of 20 cowpea genotypes in Northeastern Brazil and found a percentage of 80% coincidence between the HMGV and RPGV ordering, similar to that observed in the present study.

The three best genotypes (MNC00-595F-27, MNC05-847B-123, and BRS Tumucumaque) showed immature grain yields of 1,973, 1,844, and 1,797 kg ha^{-1}, i.e., an average superiority of 23, 15, and 12%, respectively, in relation to the general average of the nine studied environments (Table 4). These values were obtained through a process that penalizes the instability of genotypes and capitalizes their response capacity (adaptability) to improve the environment (Resende, 2007). These properties are specific of the HMRPGV statistic.

Table 3. Averages by the individual best linear unbiased prediction of genotypic effects and predicted genotypic values (u + g) free of the interaction with environments, as well as lower and higher limits of the confidence interval (LL and HL, respectively), and genetic gain of 16 cowpea (*Vigna unguiculata*) genotypes evaluated in nine environments, consisting of a combination of locations in the states of Ceará, Piauí, and Rio Grande do Norte, Brazil, and of years from 2012 to 2017.

Genotype	Genotypic effects	u + g	(LL–HL)[1]	Genetic gain (kg)
G11 – BRS Tumucumaque	292.58	1,892	1,660.05–2,123.20	292.58
G3 – MNC00-595F-27	284.47	1,883	1,651.93–2,115.08	288.52
G7 – MNC05-847B-123	167.99	1,767	1,535.46–1,998.61	248.35
G8 – MNC05-847B-126	134,05	1,733	1,501.52–1,964.67	219.77
G10 – BRS Guariba	74.22	1,673	1,441.99–1,904.83	190.66
G4 – MNC05-835-B-15	46.29	1,645	1,413.75–1,876.90	166.60
G5 – MNC05-835B-16	16.49	1,615	1,383.96–1,847.11	145.16
G13 – Paulistinha	7.20	1,606	1,374.66–1,837.81	127.91
G6 – MNC05-841B-49	-8.07	1,591	1,359.40–1,822.55	112.80
G2 – MNC00-595F-2	-17.00	1,581	1,349.97–1,813.11	99.77
G9 – MNC99-541F-15	-20.91	1,578	1,346.56–1,809.70	88.80
G1 – MNC00-586F-303-9	-120.15	1,479	1,247.32–1,710.47	71.39
G16 – Sempre Verde-CE	-179.32	1,420	1,188.14–1,651.29	52.10
G14 – Vgem Roxa-THE	-207.35	1,392	1,160.11–1,623.26	33.57
G12 – BRS Xiquexique	-225.56	1,373	1,141.91–1,605.05	16.29
G15 – Azulão-MS	-244.43	1,355	1,123.04–1,586.19	0.00
General mean (kg ha^{-1})		1,599		

[1]Confidence interval associated to the genotypic value estimates, at 5% probability.

Table 4. Stability of genotypic values by the harmonic mean of genotypic values (HMGV), adaptability of genotypic values by the relative performance of genotypic values (RPGV), adaptability and stability of genotypic values by the harmonic mean of the relative performance of genotypic values (HMRPGV), genotypic value capitalizing adaptability by the RPGV multiplied by the general mean of all environments (RPGVμ), and genotypic value penalized by instability and capitalized by adaptability by the HMRPGV multiplied by the general average of all environments (HMRPGVμ) of 16 cowpea (*Vigna unguiculata*) genotypes evaluated in nine environments, consisting of a combination of locations in the states of Ceará, Piauí and Rio Grande do Norte, Brazil, and of years from 2012 to 2017[1].

Genotype[1]	HMGV	Genotype	RPGV	RPGVμ	Genotype	HMRPGV	HMRPGVμ (kg ha^{-1})
G3	1,646	G3	1.25	2,004	G3	1.23	1,973
G7	1,551	G11	1.19	1,899	G7	1.15	1,844
G4	1,532	G7	1.16	1,859	G11	1.12	1,797
G8	1,449	G4	1.13	1,812	G8	1.11	1,773
G10	1,436	G8	1.11	1,777	G10	1.07	1,718
G5	1,417	G10	1.08	1,727	G4	1.07	1,705
G11	1,390	G5	1.05	1,686	G5	1.03	1,649
G2	1,284	G13	0.99	1,584	G2	0.98	1,563
G13	1,179	G2	0.98	1,574	G13	0.95	1,517
G9	1,178	G9	0.95	1,522	G9	0.93	1,493
G1	1,169	G6	0.94	1,512	G6	0.90	1,443
G12	1,098	G1	0.90	1,438	G1	0.88	1,413
G6	1,082	G12	0.85	1,358	G14	0.81	1,294
G14	1,034	G14	0.81	1,302	G12	0.79	1,271
G15	808	G16	0.80	1,280	G16	0.69	1,104
G16	779	G15	0.78	1,249	G15	0.66	1,054

[1]G1, MNC00-586F-303-9; G2, MNC00-595F-2; G3, MNC00-595F-27; G4, MNC05-835B-15; G5, MNC05-835B-16; G6, MNC05-841B-49; G7, MNC05-847B-123; G8, MNC05-847B-126; G9, MNC99-541F-15; G10, BRS Guariba; G11, BRS Tumucumaque; G12, BRS Xiquexique; G13, Paulistinha; G14, Vagem Roxa-THE; G15, Azulão-MS; and G16, Sempre Verde-CE.

The values of RPGV and HMRPGV showed the average superiority of the genotype in relation to the average of a given environment. Therefore, MNC00-595F-27, MNC05-847B-123, and BRS Tumucumaque were, respectively, 1.24, 1.16, and 1.13 time superior to the average of any environment where they were grown.

In general, genotypes MNC00-595F-27, MNC05-847B-123, and BRS Tumucumaque were superior regarding immature grain yield, adaptability, and stability and, therefore, could be recommended for the environments evaluated in the present study, with a lower loss of immature grain yield due to unpredictable environmental factors. According to Torres et al. (2016), genotypes that present the attributes yield, adaptability and stability, simultaneously, can be used as a selection criterion in cowpea breeding programs.

Grain color is an important visual aspect of the market of immature cowpea grains. Genotypes MNC00-595F-27 and MNC05-847B-123 stood out because they belong to the "Verde" commercial subclass, characterized by green tegument and cotyledons. According to Freire Filho et al. (2007), genotypes of this commercial subclass have high potential in this regard due to their greater capacity of preserving their green color postharvest, compared with the other commercial subclasses of cowpea.

Conclusions

1. The immature grain yield of the evaluated cowpea (*Vigna unguiculata*) genotypes interacts highly with the assessed environments, which results in a low genotypic correlation between environments.

2. The MNC00-595F-27, MNC05-847B-123, and BRS Tumucumaque genotypes present high immature grain yield, adaptability, and genotypic stability, being the most suitable for cultivation in the states of Ceará, Piauí, and Rio Grande do Norte, Brazil, or in other areas with similar soil and climatic conditions.

Acknowledgments

References

ALVARES, C.A.; STAPE, J.L.; SENTELHAS, P.C.; GONÇALVES, J.L. de M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v.22, p.711-728, 2013. DOI: https://doi.org/10.1127/0941-2948/2013/0507.

AQUINO, D.A.L. de; SANTOS, C.A.F.; SILVA, D.O.M. da. Adaptability and stability parameters for immature seeds and pods and mature dried seeds in cowpea genotypes in Brazil northeast. **African Journal of Agricultural Research**, v.11, p.5071-5079, 2016. DOI: https://doi.org/10.5897/AJAR2016.11934.

CARVALHO, L.C.B.; DAMASCENO-SILVA, K.J.; ROCHA, M. de M.; OLIVEIRA, G.C.X. Genotype x environment interaction in cowpea by mixed models. **Revista Ciência Agronômica**, v.48, p.872-878, 2017. DOI: https://doi.org/10.5935/1806-6690.20170103.

CHIORATO, A.F.; CARBONELL, S.A.M.; DIAS, L.A. dos S.; RESENDE, M.D.V. de. Prediction of genotypic values and estimation of genetic parameters in common bean. **Brazilian Archives of Biology and Technology**, v.51, p.465-472, 2008. DOI: https://doi.org/10.1590/S1516-89132008000300005.

FREIRE FILHO, F.R. (Ed.). **Feijão-caupi no Brasil**: produção, melhoramento genético, avanços e desafios. Teresina: Embrapa Meio-Norte, 2011. 84p.

FREIRE FILHO, F.R.; RIBEIRO, V.Q.; RODRIGUES, J.E.L.F.; VIEIRA, P.F.M.J. A cultura: aspectos socioeconômicos. In: VALE, J.C. do; BERTINI, C.; BORÉM, A. (Ed.). **Feijão-caupi**: do plantio à colheita. Viçosa: Ed. da UFV, 2017. p.9-34.

FREIRE FILHO, F.R.; ROCHA, M. de M.; RIBEIRO, V.Q.; RAMOS, S.R.R.; MACHADO, C. de F. Novo gene produzindo cotilédone verde em feijão-caupi. **Revista Ciência Agronômica**, v.38, p.286-290, 2007.

FREITAS, T.G.G. de; SILVA, P.S.L. e; DOVALE, J.C.; SILVA, E.M. da. Green bean yield and path analysis in cowpea landraces. **Revista Caatinga**, v.29, p.866-877, 2016. DOI: https://doi.org/10.1590/1983-21252016v29n411rc.

RESENDE, M.D.V. de. **Genética biométrica e estatística no melhoramento de plantas perenes**. Brasília: Embrapa Informação Tecnológica; Colombo: Embrapa Florestas, 2002. 975p.

RESENDE, M.D.V. de. **Matemática e estatística na análise de experimentos e no melhoramento genético**. Colombo: Embrapa Florestas, 2007. 561p.

RESENDE, M.D.V. de; DUARTE, J.B. Precisão e controle de qualidade em experimentos de avaliação de cultivares. **Pesquisa Agropecuária Tropical**, v.37, p.182-194, 2007.

ROCHA, M. de M.; ANDRADE, F.N.; GOMES, R.L.F.; FREIRE FILHO, F.R.; RAMOS, S.R.R.; RIBEIRO, V.Q. Adaptabilidade e estabilidade de genótipos de feijão-caupi quanto à produção de grãos frescos, em Teresina-PI. **Revista Científica Rural**, v.14, p.40-55, 2012.

ROCHA, M. de M.; DAMASCENO-SILVA, K.J.; MENEZES JÚNIOR, J.A. de. Cultivares. In: VALE, J.C. do; BERTINI, C.; BORÉM, A. (Ed.). **Feijão-caupi**: do plantio à colheita. Viçosa: Ed. da UFV, 2017a. p. 113-142.

ROCHA, M. de M.; DAMASCENO-SILVA, K.J.; MENEZES-JÚNIOR, J.A.N. de; CARVALHO, H.W.L. de; COSTA, A.F. da; LIMA, J.M.P. de; SANTOS, J.F. dos; BERTINI, C.H.C. de M.; PASSOS, A.R.; MORAIS, O.M. Yield adaptability and stability of semi-erect cowpea genotypes in the Northeast region of Brazil by REML/BLUP. **Revista Ciência Agronômica**, v.48, p.862-871, 2017b. Número especial. DOI: https://doi.org/10.5935/1806-6690.20170102.

ROCHA, M. de M.; DAMASCENO-SILVA, K.J.; MENEZES-JÚNIOR, J.A.N. de; CARVALHO, H.W.L. de; COSTA, A.F. da; LIMA, J.M.P. de; SANTOS, J.F. dos; BERTINI, C.H.C. de M.; PASSOS, A.R.; MORAIS, O.M. Yield adaptability and stability of semi-prostate cowpea genotypes in the Northeast region of Brazil by REML/BLUP. **Revista Ciência Agronômica**, v.48, p.879-888, 2017c. Número especial. DOI: https://doi.org/10.5935/1806-6690.20170104.

SANTOS, A. dos; CECCON, G.; TEODORO, P.E.; CORREA, A.M.; ALVAREZ, R. de C.F.; SILVA, J.F. da; ALVES, V.B. Adaptability and stability of erect cowpea genotypes via REML/BLUP and GGE Biplot. **Bragantia**, v.75, p.299-306, 2016. DOI: https://doi.org/10.1590/1678-4499.280.

SILVA, E.F. da; BARROS JÚNIOR, A.P.; SILVEIRA, L.M. da; SANTANA, F.M. de S.; SANTOS, M.G. dos. Avaliação de cultivares de feijão-caupi irrigado para produção de grãos verdes em Serra Talhada-PE. **Revista Caatinga**, v.26, p.21-26, 2013.

SOUSA, J.L.M.; ROCHA, M. de M.; SILVA, K.J.D. e; NEVES, A.C. das; SOUSA, R.R. de. Potencial de genótipos de feijão-caupi para o mercado de vagens e grãos verdes. **Pesquisa Agropecuária Brasileira**, v.50, p.392-398, 2015. DOI: https://doi.org/10.1590/S0100-204X2015000500006.

SOUZA, K.N. de; TORRES FILHO, J.; BARBOSA, L.S.; SILVEIRA, L.M. da. Avaliação de genótipos de feijão-caupi para produção de grãos verdes em Mossoró-RN. **Colloquium Agrariae**, v.15, p.9-14, 2019. DOI: https://doi.org/10.5747/ca.2019.v15.n1.a265.

TORRES FILHO, J.; OLIVEIRA, C.N.G. dos S.; SILVEIRA, L.M. da; NUNES, G.H. de S.; SILVA, A.J.R. da; SILVA, M.F.N. da. Genotype by environment interaction in green cowpea analyzed via mixed models. **Revista Caatinga**, v.30, p.687-697, 2017. DOI: https://doi.org/10.1590/1983-21252017v30n317rc.

TORRES, F.E.; TEODORO, P.E.; RODRIGUES, E.V.; SANTOS, A.; CORRÊA, A.M.; CECCON, G. Simultaneous selection for cowpea (*Vigna unguiculata* L.) genotypes with adaptability and yield stability using mixed models. **Genetics and Molecular Research**, v.15, gmr.15028272, 2016. DOI: https://doi.org/10.4238/gmr.15028272.

TORRES, F.E.; TEODORO, P.E.; SAGRILO, E.; CECCON, G.; CORREA, A.M. Interação genótipo x ambiente em genótipos de feijão-caupi semiprostrado via modelos mistos. **Bragantia**, v.74, p.255-260, 2015. DOI: https://doi.org/10.1590/1678-4499.0099.