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Scientific Article

Adaptability and stability of biomass sorghum genotypes using GGE Biplot

Adaptabilidade e estabilidade de genótipos de sorgo biomassa pelo método GGE Biplot

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ABSTRACT – The objective of this study was to evaluate the agronomic performance and select biomass sorghum genotypes for growing in different regions of Brazil based on adaptability and stability analysis using the GGE biplot method. The 25 genotypes evaluated were from trials of value for cultivation and use (VCU) of biomass sorghum of the Brazilian Agricultural Research Corporation (Embrapa Maize and Sorghum) Breeding Program, conducted in eight locations across Brazil (Sobral, CE; Jaguariúna and Narandiba, SP; Nova Porteirinha and Sete Lagoas, MG; Planaltina, DF; Vilhena, RO; and Terra Rica, PR) during the 2021-2022 crop season. A randomized block experimental design with three replications was used. The following traits of were subjected to joint analysis of variance: plant height, flowering, and fresh and dry matter yields. The confirmation of genotype-by-environment interaction (G×E) was followed by adaptability and stability analysis using the GGE biplot method for all traits. The adjusted means were used to obtain the mean clustering using the Scott-Knott test ($p < 0.05$). Biomass sorghum genotypes showed a longer growth cycle, taller plants, and higher biomass yield than forage sorghum genotypes. The experimental sorghum hybrids 202129B014 and 202129B016 and the commercial hybrid BRS 716 can be recommended for fresh and dry matter production in all tested environments due to their high adaptability and stability.

Keywords: *Sorghum bicolor*. Plant breeding. Mega-environments. Forage.

RESUMO – O objetivo do estudo foi avaliar o desempenho agronômico e selecionar genótipos de sorgo biomassa para diferentes regiões do Brasil a partir da análise de adaptabilidade e estabilidade pelo método GGE Biplot. Foram avaliados 25 genótipos, que constituíram os ensaios de valor de cultivo e uso (VCU's) de sorgo biomassa do Programa de Melhoramento da Embrapa Milho e Sorgo, conduzido em oito locais do Brasil (Sobral-CE, Jaguariúna-SP, Nova Porteirinha-MG, Planaltina-GO, Sete Lagoas-MG, Narandiba-SP, Vilhena-RO e Terra Rica-PR), na safra de 2021/2022. O delineamento experimental foi em blocos casualizados, com três repetições. Foram realizadas as análises de variância conjuntas para as características altura de plantas, florescimento e produtividades de matéria verde e seca. Constada interação (GxA), procedeu-se a análise de adaptabilidade e estabilidade pelo método de GGE Biplot, para todas as características. Com os valores de médias ajustadas, foram obtidos os agrupamentos de médias pelo teste de Scott-Knott ($p < 0.05$). Os genótipos de sorgo biomassa apresentam maior ciclo, bem como altura e produtividade de biomassa superior a genótipos de sorgo forrageiro. Os híbridos experimentais 202129B014 e 202129B016, bem como o híbrido comercial BRS 716 podem ser recomendados para todos os ambientes, pois apresentam alta adaptabilidade e estabilidade para todos os ambientes para a produção de matéria verde e seca.

Palavras-chave: *Sorghum bicolor*. Melhoramento de plantas. Mega-ambientes. Forragem.

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INTRODUCTION

Biomass sorghum [*Sorghum bicolor* (L). Moench] has significant potential for producing high-quality silage for ruminant feed (RAMOS et al., 2021; QUEIROZ et al., 2022; ROSA et al., 2022). This potential is mainly due to the higher biomass production of biomass sorghum compared to forage sorghum cultivars. Castro et al. (2015) evaluated 14 photoperiod-sensitive biomass sorghum hybrids in three locations of the state of Minas Gerais, Brazil, and found fresh matter yields of up to 124.3 Mg ha^{-1}, whereas two forage sorghum cultivars presented a maximum yield of 56.5 Mg ha^{-1}. Delgado et al. (2019) also found higher fresh matter production for photoperiod-sensitive biomass sorghum hybrids compared to forage sorghum cultivars.

The high fresh and dry matter yields of biomass sorghum plants are connected to sensitivity to photoperiod. Photoperiod-sensitive sorghum genotypes flower only under short-day conditions, with less than 12 hours and 20 minutes of light. Forage sorghum genotypes flower approximately 60 to 80 days after sowing, whereas biomass sorghum genotypes maintain the apical bud until days shorten enough to induce flower bud differentiation, which typically occurs 120 to 160 days after sowing when sown between November and December in Brazil (PARRELLA et al., 2010; PARRELLA et al., 2014). Photoperiod-sensitive sorghum genotypes have longer growth cycle under these conditions and, consequently, accumulate more fresh and dry matter by the end of the cycle. Sorghum has been an alternative to maize crops for silage production in some semiarid regions due to its resistance to water deficit and high temperatures and its wider planting window (BEHLING NETO et al., 2017; SILVA et al. 2016). Therefore, growing biomass sorghum is significantly advantageous by ensuring a greater availability of forage throughout the year.

Biomass sorghum genotypes are annually subjected to trials of value for cultivation and use in several regions of Brazil by the Brazilian Agricultural Research Corporation (Embrapa Maize and Sorghum) Breeding Program. The diverse environmental conditions in which these trials are conducted have resulted in a significant genotype-environment interaction (G×E). This presents a significant challenge for breeders to define recommendations of cultivars, as the best genotype in one environment does not necessarily maintain the same performance in another. Thus, studies on adaptability and stability are essential to more precisely detail information about the response of each genotype to environmental variations and, consequently, reduce the risks of recommendation of new cultivars. Adaptability is defined as the genotype's ability to respond to environmental stimuli, while stability is defined as the genotype's ability to exhibit predictable performance in different environments (BORÉM; MIRANDA, 2009).

Several methodologies have been described for evaluating G×E and estimating adaptability and stability parameters, focusing on making the selection and recommendation of new genotypes more reliable (MENEZES et al., 2015). GGE biplot analysis (genotype and G×E) is a method proposed by Yan et al. (2000) that considers the main effect of the genotype plus the genotype-environment interaction. It is a graphical statistical method that allows for the selection of representative and discriminative environments and the identification of the most adapted and stable genotypes and mega-environments (YAN, 2011). A mega-environment is formed by subdividing test environments into relatively homogeneous groups based on the performance of a group of genotypes (SILVA et al., 2021).

The GGE biplot analysis enables a better investigation of the variation among biomass sorghum genotypes and, consequently, the selection of those better adapted to the highest number of test environments, with stable fresh and dry matter production. Therefore, the objectives of this study were to evaluate the production performance, estimate adaptability and stability, and investigate mega-environments for the selection of better adapted and more stable biomass sorghum genotypes in different regions of Brazil, using the GGE biplot method.

MATERIAL AND METHODS

Twenty-five sorghum genotypes from the Brazilian Agricultural Research Corporation (Embrapa Maize and Sorghum) Breeding Program were evaluated, including four commercial hybrids used as controls: two forage sorghum hybrids (BRS 658 and Volumax) and two biomass sorghum hybrids (BRS 716 and AGRI002E). The other 21 genotypes are experimental biomass sorghum genotypes developed and selected by the breeding program (Table 1), which were evaluated in value for cultivation and use (VCU) trials during the 2021-2022 crop season. The experiments were conducted in eight locations across Brazil (Table 2).

A randomized block design with 25 genotypes and three replications was used for each location (environment). Experimental plots consisted of two 5-meter rows spaced 0.7 m apart, except for Terra Rica (PR) and Vilhena (RO), where the spacing between rows was 0.45 and 0.6 m, respectively. The planting density was 5.0 plants m^{-1}, resulting in a population of 71,430 plants ha^{-1}, except for Terra Rica and Vilhena (111,110 and 83,330 plants ha^{-1}, respectively).

Supplemental irrigation was applied during the growth cycle using a conventional sprinkler system. Soil fertilizers were applied at planting and as topdressing based on soil analyses. Cultural practices and plant protection measures were carried according to the needs of the crop, specific for each location. Sorghum seeds were sown in November and December 2021, except in Sobral, CE, where the sowing was carried out in February 2022 (second crop).

The sorghum plants were evaluated for plant height, flowering, and fresh and dry matter yields. Plant height was measured from the ground level to the panicle tip at harvest in six plants, obtaining the mean height (m). Flowering was determined by counting the number of days from sowing until 50% of the plants in the experimental plots exhibited pollen shedding from flowers in the upper third of the panicle.

Fresh matter yield (FMY) was determined by weighing the aboveground portion of all plants in the plot; the plants were cut 10 cm above the ground level at the grain physiological maturity and the obtained values were converted to Mg ha^{-1}. Dry matter yield (DMY) was determined at harvest, using plant samples of approximately 0.5 kg, which were placed in a forced-air oven at 65 °C for 48 hours, and weighed. The ratio between the final and initial weight of the sample was converted to percentage of dry matter in the sample. DMY values were multiplied by the percentage of dry matter to obtain the DMY in Mg ha^{-1}.

Plant height and fresh matter yield were evaluated in all experimental locations. However, flowering was not evaluated in Sete Lagoas, Narandiba, and Terra Rica, and dry matter yield was not evaluated in Narandiba, Vilhena, and Terra Rica, due to operational challenges inherent to multi-environment experiments.

Table 1. Description of the 25 genotypes evaluated in value for cultivation and use trials of biomass sorghum, including type, origin, and sensitivity to photoperiod, during the 2021-2022 crop season.

Code	Genotype	Cultivar	Origin	Classification	Photoperiod
G1	202129B001	Experimental hybrid	Embrapa	Biomass	Sensitive
G2	202129B002	Experimental hybrid	Embrapa	Biomass	Sensitive
G3	202129B003	Experimental hybrid	Embrapa	Biomass	Sensitive
G4	202129B004	Experimental hybrid	Embrapa	Biomass	Sensitive
G5	202129B005	Experimental hybrid	Embrapa	Biomass	Sensitive
G6	202129B006	Experimental hybrid	Embrapa	Biomass	Sensitive
G7	202129B007	Experimental hybrid	Embrapa	Biomass	Sensitive
G8	202129B008	Experimental hybrid	Embrapa	Biomass	Sensitive
G9	202129B009	Experimental hybrid	Embrapa	Biomass	Sensitive
G10	202129B010	Experimental hybrid	Embrapa	Biomass	Sensitive
G11	202129B011	Experimental hybrid	Embrapa	Biomass	Sensitive
G12	202129B012	Experimental hybrid	Embrapa	Biomass	Sensitive
G13	202129B013	Experimental hybrid	Embrapa	Biomass	Sensitive
G14	202129B014	Experimental hybrid	Embrapa	Biomass	Sensitive
G15	202129B015	Experimental hybrid	Embrapa	Biomass	Sensitive
G16	202129B016	Experimental hybrid	Embrapa	Biomass	Sensitive
G17	202129B017	Experimental hybrid	Embrapa	Biomass	Sensitive
G18	CMSXS7200	Variety	Embrapa	Biomass	Sensitive
G19	CMSXS7500	Experimental hybrid	Embrapa	Biomass	Sensitive
G20	CMSXS7501	Experimental hybrid	Embrapa	Biomass	Sensitive
G21	CMSXS7502	Experimental hybrid	Embrapa	Biomass	Sensitive
G22	BRS716	Hybrid commercial	Embrapa	Biomass	Sensitive
G23	AGRI002E	Hybrid commercial	Agricomseeds	Biomass	Sensitive
G24	BRS658	Hybrid commercial	Embrapa	Forage	Insensitive
G25	Volumax	Hybrid commercial	Agroceres	Forage	Insensitive

Table 2. Geographical description of the locations in Brazil where the value for cultivation and use trials for biomass sorghum were conducted during the 2021-2022 crop season.

Code	Locations	Latitude	Longitude	Altitude
SOB	Sobral, CE	3°40'58"S	40°21'4"W	66 m
JAG	Jaguariúna, SP	22°42'20"S	46°59'09"W	584 m
NP	Nova Porteirinha, MG	15°48'13"S	43°19'03"W	510 m
PLA	Planaltina, DF	15°27'10"S	47°36'51"W	944 m
SL	Sete Lagoas, MG	19°27'57"S	44°14'49"W	767 m
NA	Narandiba, SP	22°24'38"S	51°31'19"W	419 m
VIL	Vilhena, RO	12°44'26"S	60°08'45"W	612 m
TR	Terra Rica, PR	22°42'35"S	52°37'13"W	420 m

Statistical analyses were performed using the statistical software GENES®. Data from the evaluated traits were subjected to joint analysis of variance based on the environments in which each trait was evaluated. The genetic-statistical model used was $Y_{ijk} = m + G_i + B/A_{jk} + A_j + GA_{ij} + E_{ijk}$, with fixed genotype effect and random environment effect, where Y_{ijk} is the the observation of the trait in the k-th block, evaluated within the j-th environment in the i-th genotype; m is the overall mean; G_i is the effect of i-th genotype; B/A_{jk} is the effect of k-th block within the j-th environment; A_j is the effect of the j-th environment; GA_{ij} is the effect of the interaction between the i-th genotype and the j-th environment; and E_{ijk} is the experimental error associated with the observations of order ijk. The adjusted means were used to obtain the mean clustering using the Scott-Knott test ($p < 0.05$). Confirmation genotype-by-environment interaction (G×E) was followed by an analysis of adaptability and stability through the GGE biplot method (YAN et al., 2000), using the R software (R CORE TEAM, 2016). The model used was $\gamma_{ij} = \mu + \beta_j + \gamma_{1\varepsilon i1pj1} + \gamma_{2\varepsilon i2pj2} + \varepsilon_{ijk}$, where γ_{ij} is the trait evaluated for genotype i in the environment j; μ is the overall mean of observations; β_j is the main effect of the environment; γ_1 and γ_2 are the errors associated with the first (PC1) and second principal component (PC2), respectively;$\varepsilon_1$and $\varepsilon_1$are the values of PC1 and PC2, respectively, for the genotype of order i; $pj1$ and $pj2$ are the values of PC1 and PC2, respectively, for the environment of order j; and ε_{ijk} is the error associated with the model of the i-th genotype and j-th environment (R CORE TEAM, 2016).

This methodology presents graphs with the first two principal components (PC1 and PC2) derived from the singular value decomposition of genotype (G) effects and genotype-by-environment interaction (G×E) effects. PC1 indicates that the adaptability of genotypes has high correlation with biomass yield, whereas PC2 indicates phenotypic stability, meaning that genotypes with PC2 values closer to zero are the most stable (YAN et al., 2000).

RESULTS AND DISCUSSION

According to the analysis of variance, the genotype-by-environment interaction (G×E) was significant at 1% significance level for all evaluated traits, denoting different responses of genotypes to environmental variations. These results indicate genetic variability among the evaluated sorghum genotypes and the possibility of selecting genotypes of interest for the different tested environments.

Delgado et al. (2019) studied biomass sorghum genotypes and found significant G×E, mainly for traits related to biomass production and a significant environmental effect, which was attributed to macroenvironmental differences, such as climate, soil, altitude, and mainly latitude, which directly affects photoperiod and, consequently, the growth period until flower differentiation. Castro et al. (2015) found significant G×E for flowering, plant height, number of tillers, and fresh matter production in biomass sorghum hybrids grown in Lavras, Uberlândia, and Sete Lagoas, in the state of Minas Gerais (MG), Brazil.

The results of the mean clustering test for plant height showed that the overall means of most experimental biomass sorghum genotypes were equal or similar to those of photoperiod-sensitive commercial hybrids (AGRI002E and BRS716) (Table 3). The mean PH was higher than 4 meters for most genotypes, except for brown midrib genotypes (CMSXS7200, CMSXS7500, CMSXS7501, and CMSXS7502). The mean (GE) of biomass sorghum genotypes varied from 3.46 m (in Terra Rica) and 5.20 m (in Vilhena).

Selecting sorghum genotypes with tall plants can be a strategy to select genotypes with higher biomass production. Castro et al. (2015) found strong positive correlation between plant height and dry and fresh matter yields in biomass sorghum genotypes. However, very tall sorghum plants are more susceptible to lodging, mainly in regions with strong winds.

The experimental biomass sorghum genotypes showed higher plant heights than the controls (Volumax and BRS 658) in all environments. This is attributed to the sensitivity of biomass sorghum genotypes to photoperiod (PARRELLA et al., 2010). Biomass sorghum genotypes are short-day plants, meaning that they need long nights for flowering. The critical photoperiod for biomass sorghum is 12 hours and 20 minutes; thus, days with photoperiod equal to or longer than this critical limit allows biomass sorghum plants to continue growing without differentiating to the reproductive stage. Most regions in Brazil have photoperiod equal to or longer than 12 hours and 20 minutes during the spring-summer crop season. Thus, when biomass sorghum is grown in the spring-summer crop season, with sowing between October and December, plants can continue vegetative growth and only begin flowering in March of the following year (PARRELLA et al., 2010; PARRELLA et al., 2014). The forage sorghum used as controls were little affected by the photoperiod during flower differentiation, flowering between 60 and 90 days after sowing. The number of days to flowering for the genotypes (Table 4) denotes the difference in cycles between photoperiod-sensitive biomass sorghum genotypes and forage sorghum genotypes (Volumax and BRS 658).

The experimental biomass sorghum genotypes had a mean number of days to flowering of 119, higher than the maximum found for the controls (forage sorghum), which was 92 in Jaguariúna for the cultivar Volumax (Table 4). The experimental genotypes flowered between 107 days (genotype 202129B012 in Vilhena) and 152 days (genotype 202129B005 in Nova Porteirinha), except in Sobral.

The shortest time to flowering (Sobral) was due to the sowing season, as sorghum was sown as a second crop, in February. Thus, the longest period of vegetative development occurred between the autumn equinox (March) and the winter solstice (June), a period with the shortest photoperiod in the Southern Hemisphere, favoring early flowering in photoperiod-sensitive sorghum plants. Castro et al. (2015) conducted tests in the state of Minas Gerais and found that biomass sorghum genotypes sown in Uberlândia in March exhibited early flowering, shorter plants, and lower fresh matter yield compared to tests with sowing in November in Sete Lagoas and Lavras.

Meki et al. (2017) evaluated the performance of biomass sorghum hybrids in Maui (HI) and Temple (TX), USA (Northern Hemisphere) and found that the plants were affected by planting season and photoperiod. In Temple, biomass sorghum was sown in April, when the photoperiod is longer than 12 hours and 20 minutes, and showed satisfactory performance, with plant heights exceeding 3 m and a dry matter yield of 37.4 Mg ha^{-1}. In Maui, the biomass sorghum was sown in September, when the photoperiod is shorter than 12 hours and 20 minutes, and exhibited early flowering (approximately 90 days after sowing), with plant height and biomass yield and 44% and 66% lower, respectively.

Table 3. Plant height (m) of 25 sorghum genotypes evaluated in Planaltina, DF (PL), Sete Lagoas, MG (SL), Narandiba, SP (NA), Nova Porteirinha, MG (NP), Vilhena, RO (VIL), Jaguariúna, SP (JAG), Sobral, CE (SOB), and Terra Rica, PR (TR), Brazil, during the 2021-2022 crop season.

Genotypes	PL	SL	NA	NP	VIL	JAG	SOB	TR	Mean
202129B001	4.46 Bc	4.65 Bd	3.35 Dc	4.80 Ba	5.10 Ab	3.54 Db	3.47 Db	3.93 Ca	4.16
202129B002	4.52 Bc	4.92 Bc	3.73 Cb	4.86 Ba	5.30 Aa	4.03 Cb	3.66 Cb	3.70 Ca	4.34
202129B003	4.53 Bc	4.94 Ac	4.18 Ca	5.10 Aa	5.10 Ab	3.89 Cb	3.56 Db	3.93 Ca	4.40
202129B004	4.64 Bc	4.64 Bd	4.18 Ca	5.13 Aa	5.53 Aa	4.16 Ca	3.85 Ca	3.77 Ca	4.49
202129B005	4.51 Bc	4.18 Ce	4.13 Ca	4.83 Ba	5.73 Aa	4.39 Ba	3.97 Ca	3.73 Ca	4.43
202129B006	5.44 Aa	5.79 Aa	4.13 Ba	5.62 Aa	5.63 Aa	4.18 Ba	4.12 Ba	3.50 Cb	4.80
202129B007	4.61 Ac	5.02 Ac	3.57 Bc	4.97 Aa	4.90 Ab	3.82 Bb	3.53 Bb	3.83 Ba	4.28
202129B008	4.71 Bc	5.28 Ab	4.41 Ba	5.03 Aa	5.15 Ab	4.09 Cb	3.66 Db	3.47 Db	4.48
202129B009	4.59 Cc	5.27 Bb	3.89 Db	4.95 Ca	5.70 Aa	3.79 Db	3.62 Db	3.42 Db	4.40
202129B010	4.66 Bc	4.95 Bc	4.15 Ca	5.10 Aa	5.43 Aa	3.65 Db	3.65 Db	3.52 Db	4.39
202129B011	4.74 Bc	5.35 Ab	4.13 Ca	5.22 Aa	5.60 Aa	4.41 Ca	3.69 Db	3.50 Db	4.58
202129B012	4.55 Cc	5.55 Aa	4.19 Ca	5.05 Ba	5.50 Aa	4.65 Ca	3.67 Db	3.73 Da	4.61
202129B013	4.55 Cc	4.93 Bc	3.73 Db	5.10 Ba	5.43 Aa	3.92 Db	3.76 Db	4.00 Da	4.43
202129B014	4.94 Bb	5.22 Bb	4.03 Ca	5.07 Ba	5.57 Aa	4.42 Ca	3.70 Db	3.30 Db	4.53
202129B015	4.49 Cc	5.22 Bb	4.20 Ca	5.02 Ba	5.57 Aa	4.16 Ca	3.93 Da	3.53 Db	4.52
202129B016	4.78 Bc	5.51 Aa	4.34 Ca	5.07 Ba	5.30 Aa	3.90 Db	3.70 Db	3.67 Da	4.53
202129B017	4.56 Bc	4.83 Bc	4.10 Ca	4.98 Aa	5.17 Ab	4.24 Ca	3.58 Db	3.50 Db	4.37
CMSXS7200	3.12 Cd	3.55 Bf	2.89 Cd	3.98 Ab	3.20 Cd	2.87 Cd	3.13 Cc	2.21 Dd	3.12
CMSXS7500	4.19 Bc	4.17 Be	3.05 Cd	4.42 Bb	4.83 Ab	3.24 Cc	3.12 Cc	2.80 Cc	3.73
CMSXS7501	4.47 Bc	4.30 Be	3.18 Cc	4.27 Bb	5.00 Ab	3.36 Cc	3.37 Cc	2.60 Dc	3.82
CMSXS7502	4.16 Ac	4.46 Ad	3.32 Cc	4.38 Ab	4.43 Ac	3.67 Bb	3.21 Cc	3.07 Cb	3.84
BRS716	5.01 Ab	5.16 Ac	4.36 Ba	4.83 Aa	5.20 Ab	4.36 Ba	4.01 Ca	3.70 Ca	4.58
AGRI002E	5.00 Bb	5.23 Ab	4.44 Ca	4.93 Ba	5.63 Aa	4.73 Ba	4.27 Ca	3.93 Da	4.77
BRS658	2.62 Be	2.75 Bg	3.23 Ac	2.75 Bc	2.78 Be	2.22 Ce	1.81 Dd	1.72 Dd	2.49
Volumax	2.59 Ae	2.77 Ag	2.70 Ad	2.55 Ac	2.68 Ae	2.07 Be	1.86 Bd	1.93 Bd	2.39
Mean (VCU)	4.42	4.74	3.82	4.72	5.02	3.83	3.52	3.36	4.18
Mean (GE)	4.53	4.89	3.85	4.90	5.20	3.92	3.62	3.46	4.30
Mean (T)	3.81	3.98	3.68	3.77	4.07	3.34	2.99	2.82	3.56

VCU = value for cultivation and use; GE = genotype-by-environment interaction; T = trait. Means followed by the same uppercase letter in the rows or lowercase letter in the columns are not significantly different from each other by the Scott-Knott test at a 5% significance level.

Table 4. Number of days to flowering for 25 sorghum genotypes evaluated in five locations in Brazil during the 2021-2022 crop season.

Genotypes	Planaltina	Nova Porteirinha	Vilhena	Jaguariúna	Sobral	Mean
202129B001	127 Bd	127 Bd	114 Ce	132 Ac	76 Da	115
202129B002	137 Bb	145 Ab	124 Cc	144 Aa	75 Da	125
202129B003	124 Bd	116 Ce	110 Df	132 Ac	74 Ea	111
202129B004	127 Ad	127 Ad	115 Be	130 Ac	74 Ca	115
202129B005	148 Aa	152 Aa	130 Bb	147 Aa	76 Ca	131
202129B006	131 Bc	131 Bd	114 Ce	137 Ab	75 Da	118
202129B007	126 Bd	126 Bd	114 Ce	132 Ac	72 Da	114
202129B008	123 Bd	127 Ad	111 Cf	130 Ac	75 Da	113
202129B009	127 Ad	130 Ad	114 Be	132 Ac	77 Ca	116
202129B010	128 Ad	127 Ad	112 Bf	130 Ac	74 Ca	114
202129B011	141 Ab	145 Ab	130 Bb	134 Bb	77 Ca	126
202129B012	126 Bd	119 Ce	107 Df	137 Ab	75 Ea	113
202129B013	127 Ad	128 Ad	111 Bf	132 Ac	74 Ca	114
202129B014	141 Ab	145 Ab	128 Cb	134 Bb	77 Da	125
202129B015	138 Bb	140 Bc	127 Cb	144 Aa	79 Da	126
202129B016	124 Ad	127 Ad	112 Bf	130 Ac	72 Ca	113
202129B017	134 Ac	131 Ad	121 Bd	137 Ab	78 Ca	120
CMSXS7200	148 Aa	149 Aa	148 Aa	147 Aa	80 Ba	134
CMSXS7500	134 Ac	137 Ac	128 Bb	137 Ab	75 Ca	122
CMSXS7501	137 Bb	148 Aa	130 Cb	137 Bb	76 Da	125
CMSXS7502	123 Bd	126 Bd	117 Ce	130 Ac	76 Da	114
BRS716	133 Bc	140 Ac	125 Cc	134 Bb	79 Da	122
AGRI002E	132 Bc	139 Ac	118 Cd	137 Ab	79 Da	121
BRS658	81 Af	71 Bf	61 Cg	83 Ae	64 Ca	72
Volumax	86 Be	74 Cf	65 Dg	92 Ad	64 Da	76
Mean (VCU)	128	129	115	132	75	116
Mean (GE)	132	133	120	135	76	119
Mean (T)	108	106	92	112	71	98

VCU = value for cultivation and use; GE = genotype-by-environment interaction; T = trait. Means followed by the same uppercase letter in the rows or lowercase letter in the columns are not significantly different from each other by the Scott-Knott test at a 5% significance level.

Sorghum, conserved as silage, is an important alternative for ruminant feeding during drought periods in several regions of Brazil. Therefore, a high sorghum biomass yield during the summer ensures the feed availability during dry months. Fresh matter yield (FMY) of experimental biomass sorghum genotypes varied between 53.47 Mg ha^{-1} (CMSXS7200) and 87.11 Mg ha^{-1} (202129B014), with an overall mean of 74.46 Mg ha^{-1}. The experimental genotypes 202129B014 (G14), 202129B015 (G15), and 202129B016 (G16), and the cultivar BRS 716 (G22), showed overall means higher than 83 Mg ha^{-1}. The highest yields of photoperiod-sensitive genotypes (G1 to G23) were found in Narandiba, varying from 98.02 to 163.11 Mg ha^{-1} (Table 5).

Dry matter yield (DMY) of experimental biomass sorghum genotypes varied from 11.80 (CMSXS7200) to 28.50 Mg ha^{-1} (202129B014), with an overall mean of 21.68 Mg ha^{-1} (Table 6). The highest DMY was 41.89 Mg ha^{-1}, obtained for the genotype 202129B007 in Nova Porteirinha. FMY and DMY of experimental biomass sorghum genotypes were, in general, higher than those of the two forage sorghum cultivars evaluated (BRS658 and Volumax). The lower yields found for the forage sorghum cultivars are connected to their photoperiod insensibility, which results in shorter cycles (Table 4), shorter plants (Table 3) and, consequently, lower biomass production (Tables 5 and 6).

Brown midrib (BMR) mutant sorghum genotypes, characterized by brown pigments in the midrib of leaves and stems, have low lignin content in their biomasses (ALMEIDA et al., 2019). Therefore, they result in a high-quality silage, with higher digestibility for ruminants (SOUZA et al. 2024). However, among the biomass sorghum genotypes evaluated in the present study, the BMR mutants CMSXS7200, CMSXS7500, CMSXS7501, and CMSXS7502 showed the lowest FMY and DMY (Tables 5 and 6). Aguilar et al. (2015) evaluated 20 sorghum genotypes for silage and grazing and found the lowest plant heights and fresh and dry matter yields for BMR mutant genotypes. According to Awio et al. (2024), sorghum and other genotypes with BMR genes typically exhibit some inferior agronomic traits than non-mutant genotypes, including increased susceptibility to lodging and diseases and reduced biomass yield.

Most biomass sorghum genotypes presented higher potential for silage production than forage genotypes (Volumax and BRS 658), as shown by their higher FMY and DMY. The substitution of forage sorghum silage with biomass sorghum silage was evaluated in the semiarid region of Minas Gerais by Ramos et al. (2021), who found that biomass sorghum silage can fully substitute forage sorghum in the diet of crossbred cattle for milk production. Rosa et al. (2022) evaluated the nutritional quality of biomass sorghum silages (saccharine and forage) and found that biomass sorghum genotypes were suitable for forage, as they resulted in silages with good fermentation patterns and higher biomass production.

Table 5. Fresh matter yield (FMY; Mg ha^{-1}) of 25 sorghum genotypes evaluated in Planaltina, DF (PL), Sete Lagoas, MG (SL), Narandiba, SP (NA), Nova Porteirinha, MG (NP), Vilhena, RO (VIL), Jaguariúna, SP (JAG), Sobral, CE (SOB), and Terra Rica, PR (TR), Brazil, during the 2021-2022 crop season.

Genotypes	PL	SL	NA	NP	VIL	JAG	SOB	TR	Mean
202129B001	41.74Bc	82.97Ab	98.02Ac	90.38Ab	81.11Aa	44.09Ba	54.36Ba	91.60Ab	73.03
202129B002	40.63Dc	60.23Cc	134.32Ab	59.05Cc	76.11Ca	41.22Da	44.84Da	89.85Bb	68.28
202129B003	39.59Cc	71.87Bc	124.59Ab	81.00Bb	48.89Cb	32.55Ca	43.26Ca	72.48Bc	64.28
202129B004	44.92Cc	56.63Cc	128.04Ab	75.05Bc	85.56Ba	44.65Ca	51.96Ca	112.67Ab	74.93
202129B005	50.16Cb	54.20Cc	118.62Ab	70.81Bc	80.56Ba	37.46Ca	43.57Ca	108.10Ab	70.43
202129B006	102.70Ba	100.40Ba	163.11Aa	99.57Ba	88.89Ba	35.19Ca	43.36Ca	38.87Cd	84.01
202129B007	60.63Cb	90.17Bb	107.74Ac	111.81Aa	80.56Ba	45.76Ca	60.89Ca	98.22Ab	81.97
202129B008	57.46Cb	93.15Bb	159.69Aa	59.00Cc	65.00Ca	39.42Ca	49.50Ca	86.71Bc	76.24
202129B009	52.22Db	73.15Cc	126.11Ab	90.14Bb	67.22Ca	35.13Da	50.55Da	104.24Bb	74.85
202129B010	52.38Db	92.38Bb	135.29Ab	92.76Bb	70.00Ca	40.37Da	48.75Da	92.84Bb	78.1
202129B011	43.43Cc	101.21Ba	124.28Ab	95.90Bb	81.11Ba	34.27Ca	59.87Ca	83.34Bc	77.93
202129B012	87.30Ba	87.67Bb	133.24Ab	90.71Bb	73.89Ba	37.49Ca	43.19Ca	53.12Cd	75.83
202129B013	51.90Db	77.93Cb	128.47Bb	62.14Cc	59.44Ca	34.81Da	43.62Da	197.00Aa	81.91
202129B014	60.08Cb	111.28Ba	141.28Aa	114.38Ba	76.67Ca	40.33Da	49.34Da	103.55Bb	87.11
202129B015	59.84Cb	108.61Ba	127.45Ab	102.19Ba	91.67Ba	39.47Ca	54.89Ca	92.86Bb	84.62
202129B016	62.92Cb	101.48Ba	145.57Aa	92.10Bb	73.89Ca	48.10Ca	51.23Ca	92.81Bb	83.51
202129B017	49.62Cb	81.05Bb	134.00Ab	91.43Bb	81.11Ba	58.52Ca	61.92Ca	94.52Bb	81.52
CMSXS7200	25.08Cc	51.20Bc	144.89Aa	58.62Bc	51.37Bb	22.42Ca	44.01Ba	30.15Cd	53.47
CMSXS7500	42.54Cc	59.70Bc	151.92Aa	73.48Bc	54.44Bb	31.97Ca	44.41Ca	72.77Bc	66.4
CMSXS7501	45.87Cc	76.90Bb	115.64Ab	79.14Bb	54.44Cb	37.09Ca	47.27Ca	41.78Cc	62.27
CMSXS7502	44.61Dc	64.66Cc	124.93Ab	51.90Cc	52.78Cb	29.63Da	41.25Da	93.25Bb	62.88
BRS716	60.98Cb	99.09Ba	127.71Ab	116.19Aa	87.78Ba	49.66Ca	62.57Ca	91.22Bb	86.9
AGRI 002E	44.00Dc	108.10Ba	135.74Ab	80.05Cb	86.11Ca	44.85Da	53.27Da	78.61Cc	78.84
BRS658	20.79Bc	32.14Bd	58.77Ad	33.60Bd	22.22Bc	24.68Ba	25.72Ba	40.44Bd	32.29
Volumax	27.94Ac	33.62Ad	54.99Ad	34.50Ad	30.56Ac	25.76Aa	31.78Aa	28.11Ad	33.41
Mean (VCU)	50.77	78.79	125.78	80.24	68.85	38.2	48.22	83.56	71.8
Mean (GE)	53.12	80.8	131.77	82.93	71.18	38.57	49.14	88.13	74.46
Mean (T)	38.43	68.24	94.3	66.08	56.67	36.24	43.33	59.6	57.86

VCU = value for cultivation and use; GE = genotype-by-environment interaction; T = trait. Means followed by the same uppercase letter in the rows or lowercase letter in the columns are not significantly different from each other by the Scott-Knott test at a 5% significance level.

Table 6. Dry matter yield (DMY; Mg ha^{-1}) of 25 sorghum genotypes evaluated in Planaltina, DF (PL), Sete Lagoas, MG (SL), Jaguariúna, SP (JAG), Sobral, CE (SOB), and Nova Porteirinha, MG (NP), Brazil, during the 2021-2022 crop season.

Genotypes	PL	SL	JAG	SOB	NP	Mean
202129B001	12.28 Cc	31.04 Ab	14.44 Ca	20.44 Bc	33.02 Ab	22.24
202129B002	12.26 Bc	21.72 Ac	15.99 Ba	22.28 Ac	22.28 Ac	18.91
202129B003	12.07 Cc	27.91 Ab	11.66 Ca	22.17 Bc	32.08 Ab	21.18
202129B004	14.67 Bc	22.88 Ac	15.10 Ba	20.45 Ac	28.42 Ab	20.30
202129B005	17.01 Bc	22.67 Ac	12.82 Ba	18.16 Bc	27.10 Ab	19.55
202129B006	30.68 Aa	38.41 Aa	11.26 Ca	21.08 Bc	33.59 Ab	27.00
202129B007	17.65 Cb	31.52 Bb	15.65 Ca	28.41 Bb	41.89 Aa	27.02
202129B008	16.06 Bb	33.54 Ab	12.03 Ba	15.78 Bd	19.75 Bc	19.43
202129B009	16.35 Bb	26.24 Ac	10.73 Ba	29.53 Ab	31.85 Ab	22.94
202129B010	15.32 Bb	32.59 Ab	12.33 Ba	25.17 Ab	30.43 Ab	23.17
202129B011	12.78 Cc	38.04 Aa	11.66 Ca	21.72 Bc	35.93 Aa	24.03
202129B012	25.40 Aa	31.88 Ab	13.44 Ba	25.30 Ab	30.96 Ab	25.40
202129B013	15.73 Bb	26.43 Ac	11.34 Ba	24.94 Ab	22.12 Ac	20.11
202129B014	19.11 Cb	40.14 Aa	14.60 Ca	29.52 Bb	39.11 Aa	28.50
202129B015	19.36 Bb	37.85 Aa	13.51 Ba	18.41 Bc	37.88 Aa	25.40
202129B016	20.36 Bb	36.45 Aa	15.19 Ba	30.29 Ab	32.17 Ab	26.89
202129B017	14.46 Cc	25.41 Bc	18.74 Ca	38.72 Aa	31.82 Ab	25.83
CMSXS7200	6.62 Bc	13.77 Ad	8.00 Ba	14.11 Ad	16.49 Ad	11.80
CMSXS7500	12.46 Bc	18.90 Ac	11.02 Ba	13.60 Bd	23.22 Ac	15.84
CMSXS7501	10.87 Bc	19.87 Ac	10.60 Ba	14.10 Bd	19.10 Ac	14.91
CMSXS7502	10.50 Bc	18.38 Ac	8.90 Ba	21.16 Ac	14.74 Ad	14.74
BRS716	18.87 Bb	33.76 Ab	17.24 Ba	37.44 Aa	40.28 Aa	29.52
AGRI002E	16.52 Cb	43.68 Aa	14.41 Ca	20.21 Cc	28.07 Bb	24.58
BRS658	5.96 Ac	11.65 Ad	7.33 Aa	10.99 Ad	13.36 Ad	9.86
Volumax	6.56 Bc	12.53 Bd	6.16 Ba	18.43 Ac	10.85 Bd	10.91
Mean (VCU)	15.20	27.89	12.57	22.50	27.86	21.20
Mean (GE)	15.81	28.36	12.81	22.64	28.76	21.68
Mean (T)	11.98	25.41	11.28	21.77	23.14	18.71

VCU = value for cultivation and use; GE = genotype-by-environment interaction; T = trait. Means followed by the same uppercase letter in the rows or lowercase letter in the columns are not significantly different from each other by the Scott-Knott test at a 5% significance level.

Benotype-by-environment interaction is defined as the different performance of genotypes as a function of the environment (ROSA et al., 2017). This interaction challenges the selection and recommendation of new cultivars, as it does not provide complete and accurate information on the performance of each genotype under each environmental condition (TAVARES et al., 2017). Studying these interactions is essential for releasing new cultivars, as it allows for the selection of genotypes with production stability in different environments or adapted to a specific environment (DIAS et al., 2018). Thus, the risks of recommending a cultivar are lower when its ability to respond positively to environmental conditions (adaptability) and its ability to exhibit predictable performance in response to environmental variations (stability) are high.

The adaptability and stability of genotypes for FMY and DMY were evaluated through the GGE biplot method. This method, proposed by Yan et al. (2000), considers the genotype (G) and its interaction with the environment (GE) as the two most important effects in the analysis. The environment effect is analyzed simultaneously. The genotype effect in the GGE biplot is additive, the genotype-by-environment interaction (G×E) effect is multiplicative, and the analysis is carried out through principal components. This method does not separate the genotype effects from the interaction effects and provides a graphical representation and the identification of mega-environments, i.e., it makes the selection of representative and discriminative environments and indicates genotypes that are more adapted and stable for the studied environments (YAN, 2011; BATISTA et al., 2017).

The first principal component (PC1) corresponded to 53% and the second (PC2) to 27% of the variance in FMY data. PC1 corresponded to 74% and PC2 to 14% of the variance in DMY data (Figure 1). These results show a high reliability for the performance of the different genotypes in the evaluated environments, represented by graphs, as the contribution to the total variance in the genotypes performances, combined with G×E and G+G×E interactions, was higher than 70%, the minimum percentage for explanation recommended for GGE biplot analysis (YAN et al., 2000).

According Gomes et al. (2019), genotypes at the vertex of the polygon, within a mega-environment, exhibit the highest adaptability to the environments that compose this mega-environment. There was a stratification into two mega-environments for FMY (Figure 1A); the first composed by Planaltina, Narandiba, Vilhena, Nova Porteirinha, and Sete Lagoas, and the second composed by Sobral and Jaguariúna. In the first mega-environment, the genotype with the highest adaptability was 202129B006 (G6), while in the second mega -environment, the genotype 202129B014 (G14) showed the highest adaptability. The Terra Rica environment was not included in any mega-environment and was a discriminatory environment but not representative for FMY, as it was very distant from the central axis of the biplot. According to Silva et al. (2015), discriminatory but not representative environments can be useful for discarding unstable genotypes.

DMY evaluated in Sobral, Nova Porteirinha, Sete Lagoas, Planaltina, and Jaguariúna by the GGE biplot formed two mega-environments (Figure 1B); the first composed by Sete Lagoas and Planaltina, and the second composed by Nova Porteirinha and Jaguariúna. In the first mega-environment, 202129B006 (G6) was the genotype with the highest adaptability, while in the second mega-environment, the 202129B014 (G14) exhibited the highest adaptability. Genotypes that compose a sector that does not include any environments are classified as not adapted to the tested environments, meaning they exhibit inferior performance (YOKOMIZO et al., 2020). This was observed with the forage controls BRS 658 (G24) and Volumax (G25) for FMY and DMY (Figure 1).

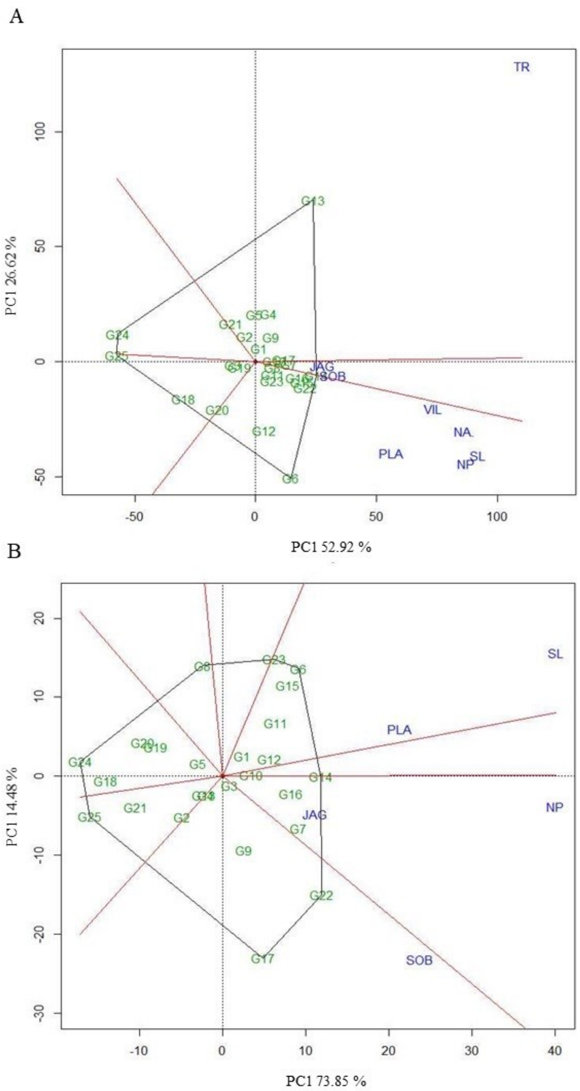

Figure 1. Mega-environments obtained by GGE biplot analysis (main effects of genotype + genotype-by-environment interaction) for fresh matter yield (Figure A) and dry matter yield (Figure B) of biomass sorghum genotypes evaluated in Sobral, CE (SOB), Jaguariúna, SP (JAG); Nova Porteirinha, MG (NP), Planaltina, DF (PLA), Sete Lagoas, MG (SL), Narandiba, SP (NA), Vilhena, RO (VIL), and Terra Rica, PR (TR), Brazil, during the 2021-2022 crop season.

The GGE biplot graph (Figure 2) enables the evaluation of genotypes for adaptability and stability based on the overall mean of environments (YAN et al., 2007; YAN, 2011). The arrow in Figure 2 indicates the environmental mean, which represents the overall mean of all environments and is defined by the mean coordinates of all evaluated environments. In this biplot, the straight line that cuts the graph more horizontally with a single arrow is referred as the mean-environment axis. This arrow points to a higher mean performance of genotypes. The line that cuts the graph more vertically corresponds to the variability of genotype performance in both directions. Thus, genotypes close to the ends of this line, in both directions, have lower stability (HONGYU et al., 2015).

The experimental genotypes 202129B006 (G6), 202129B014 (G14), 202129B015 (G15), and 202129B016

(G16), as well as the commercial hybrid BRS 716 (G22), were closer to the biplot target, indicated by the tip of the arrow and, thus, were classified as the genotypes with the highest adaptability for FMY based on the overall mean of all environments (Figure 2A). These genotypes showed mean FMY varying from 83.51 to 87.11 Mg ha^{-1} (Table 5). Genotypes 202129B006 (G6), 202129B007 (G7), 202129B014 (G14), 202129B016 (G16), and BRS 716 (G22) showed higher adaptability for DMY.

Becker (1981) ranked stability into two types: static and dynamic; static is when the genotype presents a stable response to different environments, with a small variance. This type of stability is of little agronomic interesting, since genotypes with this type of stability have a low response to environmental improvements for increased yield (e.g. favorable climate conditions and fertilizer applications). This type of stability was observed in photoperiod-sensitive genotypes [BMR mutants, CMSXS7200 (G18), CMSXS7500 (G19), CMSXS7501 (G20), and CMSXS7502 (G21)] and in the photoperiod-insensitive forage sorghum used as controls [BRS 658 (G24) and Volumax (G25)], which showed predictable results, i.e., they were stable but did not show FMY and DMY adaptability to any of the evaluated environments (Figure 2). Dynamic stability is agronomically interesting, as the genotype keeps its ability to respond to environmental stimuli and exhibits predictable performance, similar to the mean performance of all the genotypes in relation to the environments.

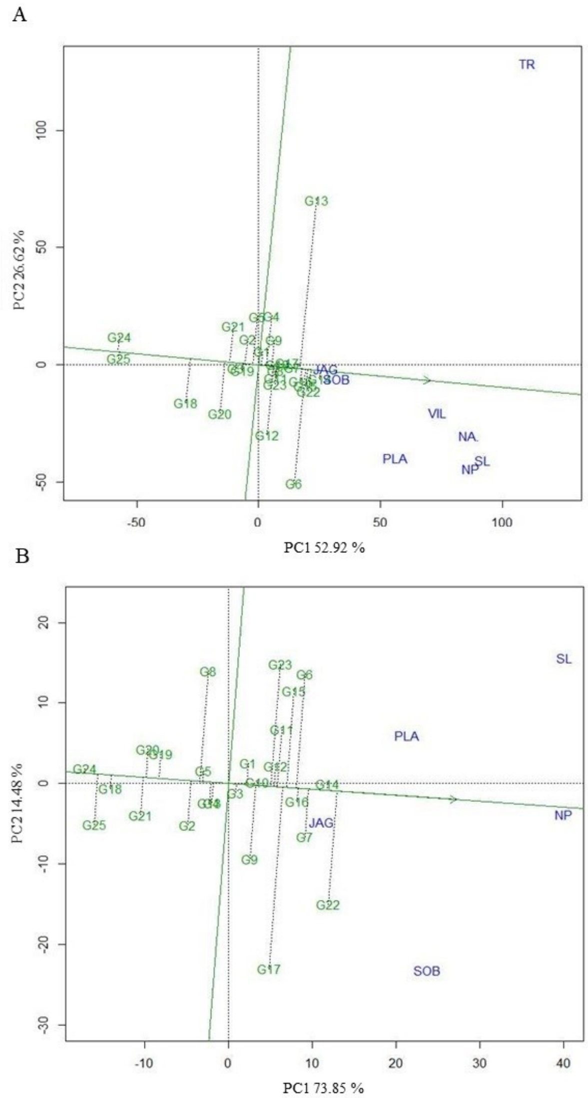

Figure 2. GGE biplot analysis (mean versus stability) for fresh matter yield (A) and dry matter yield (B) of biomass sorghum genotypes evaluated in Sobral, CE (SOB), Jaguariúna, SP (JAG); Nova Porteirinha, MG (NP), Planaltina, DF (PLA), Sete Lagoas, MG (SL), Narandiba, SP (NA), Vilhena, RO (VIL), and Terra Rica, PR (TR), Brazil, during 2021-2022 crop season.

Based on this concept of dynamic stability, genotypes 202129B014 (G14), 202129B015 (G15), 202129B016 (G16), and BRS 716 (G22) showed the highest adaptability and stability for FMY, as they were responsive to environmental conditions but stable, close to the mean-environment axis of the biplot, within the evaluated environments (Figure 2A). Similar results were found for DMY; 202129B007 (G7), 202129B014 (G14), and 202129B016 (G16) were the genotypes with the highest adaptability and stability in the studied environments.

DMY is the most interesting trait in the selection of sorghum genotypes for silage production, as it consists in the solid food fraction that can be converted into nutrients. However, FMY has higher importance for the selection of genotypes with higher adaptability and stability, as it was evaluated in all environments, providing more reliable data for selection and recommendation of the best genotypes. Castro et al. (2015) found positive and strong Pearson's correlation (0.93) between FMY and DMY for biomass sorghum genotypes. In this sense, the selection of sorghum genotypes based on adaptability and stability for FMY results in the selection of genotypes with higher DMY.

CONCLUSIONS

Two mega-environments were identified for fresh matter yield of biomass sorghum, one composed by Vilhena - RO, Narandiba - SP, Sete Lagoas - MG, Planaltina - DF, and Nova Porteirinha - MG, and another composed by Jaguariúna - SP and Sobral - CE. Two mega-environments were identified for dry matter yield, one composed by Sete Lagoas and Planaltina, and another composed by Nova Porteirinha and Jaguariúna.

The experimental biomass sorghum hybrid 202129B006 presented specific adaptability for fresh matter yield in the mega-environment composed by Planaltina, Narandiba, Vilhena, Nova Porteirinha, and Sete Lagoas, and for dry matter yield in the mega-environment composed by Sete Lagoas and Planaltina.

The experimental hybrids 202129B014 and 202129B016 and the commercial hybrid BRS 716 can be recommended for all evaluated environments, as they showed high yield, adaptability, and stability for fresh and dry matter production.

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