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Adaptability, stability and environmental stratification of genetically and nongenetically modified corn in the Cerrado[1]

Adaptabilidade, estabilidade e estratificação ambiental de milho transgênico e não transgênico no Cerrado

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HIGHLIGHTS:

Genotype-environment interaction influences the selection of new cultivars and yield increases.
Water stress combined with temperature variations has a considerable effect on crop adaptability.
Cultivars are expected to behave differently according to fertilization levels, location and growing season.

ABSTRACT: Crop yield depends on interaction between genetic and environmental factors, making it essential to study adaptability, stability and environmental stratification in order to mitigate the effects of this interaction. Four experiments were conducted to assess competition between corn cultivars in the 2018/19 growing season, two in Paraíso do Tocantins and two in Palmas, with sowing performed on November 5, 2018 and January 15, 2019. Cultivar-environment interaction was analyzed in genetically modified (GM) and non-GM commercial corn cultivars in the Vale do Araguaia region of Tocantins state (TO), Brazil, A randomized block design was used for all the experiments, in 3 × 12 factorial scheme, with three doses of nitrogen fertilizer as topdressing (50, 100 and 150 kg of N ha^{-1}) and 12 commercial cultivars (six non-GM, 1CHD, 2CV, 3CV, 4CV, 5CTH, 6CDH and six GM, 7GTH, 8GTH, 9GSH, 10GSH, 11GSH, 12GSH. For statistical analysis, the N dose in each experiment represented a different environment. The characteristic studied was grain yield, using the adaptability and stability methods as well as environmental stratification. Different responses were observed between the GM and non-GM cultivars. Most of the GM and non-GM cultivars were better adapted to favorable and unfavorable environments, respectively. All the environments exhibited similar behavior regardless of location, sowing time and the N dose used, demonstrating that fewer environments can be used in future breeding research.

Key words: *Zea mays* L., cultivar x environment interaction, grain yield

RESUMO: O rendimento da cultura depende da interação entre os fatores genéticos e ambientais, tornando-se necessário estudo de adaptabilidade, estabilidade e estratificação ambiental visando atenuar os efeitos desta interação. Neste sentido, visando estudar a interação cultivar x ambiente em cultivares comerciais de milho transgênico e não transgênico na região do Vale do Araguaia TO, foram realizados quatro ensaios de competição de cultivares implantados na safra 2018/19, sendo dois em Paraíso do Tocantins e dois em Palmas, com semeaduras realizadas em 05/11/2018 e 15/01/2019. O delineamento experimental, em cada ensaio, foi de blocos casualizados com 36 tratamentos, que foram dispostos em esquema fatorial 3 × 12, representados por três doses de adubação nitrogenada em cobertura (50, 100 e 150 kg de N ha^{-1}) e por 12 cultivares comerciais, (seis transgênicos: 1CHD, 2CV, 3CV, 4CV, 5CTH, 6CDH e seis não transgênicos: 7GTH, 8GTH, 9GSH, 10GSH, 11GSH, 12GSH). Na análise estatística, cada dose de N em cada ensaio representou um ambiente distinto. A característica estudada foi a produtividade de grãos, sendo utilizados os métodos de adaptabilidade e estabilidade, bem como a técnica de estratificação ambiental. Houve resposta diferencial entre as cultivares oriundas de tecnologias transgênicas e não transgênicas. Cultivares transgênicas e não transgênicas, em sua maioria, foram mais adaptadas aos ambientes favoráveis. e desfavoráveis, respectivamente. Houve similaridade entre ambientes oriundos de locais, épocas de semeadura e doses de N, apontando para redução de ambientes em futuros trabalhos de melhoramento.

Palavras-chave: *Zea mays* L., interação cultivar x ambiente, rendimento de grãos

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INTRODUCTION

Corn is an economically important crop in the state of Tocantins, ranking second in terms of grain production. In the 2019/20 growing season, 282,300 ha were planted, with production of 1,479,800 metric tons, representing an increase of approximately 24% in relation to the 2018/19 crop (CONAB, 2021).

Crop yield depends on an interaction between genetics, the environment and crop management factors (EMBRAPA, 2020). Thus, using technologies such as plant breeding, hybrids adapted to regional climate conditions, resistance to disease and pests, correct planting and harvesting strategies and fertilizers such as nitrogen, is essential in obtaining high yields.

In regard to fertilizers, nitrogen (N) is the mineral most needed by corn and has the most significant influence on grain yield, since it participates directly in protein and chlorophyll biosynthesis (Oliveira et al., 2020).

Environmental stratification and the identification and use of cultivars with high adaptability and stability are alternatives to mitigate the effect of interaction (C × E) (Mijone et al., 2019). Identifying similar environments streamlines breeding programs and lowers costs because it allows breeders to eliminate similar environments within each group without compromising the efficiency and precision of the selection process (Cruz & Regazzi, 2007).

Although the literature addresses cultivar-environment interaction, this study aims to analyze the effect of cultivar-environment interaction in commercial genetically modified (GM) and non-GM corn cultivars under different doses of nitrogen (topdressing) in the Vale do Araguaia region of Tocantins state (TO), Brazil, in the 2018/2019 growing season.

MATERIAL AND METHODS

Four experiments were conducted to assess competition between cultivars in the 2018/19 growing season in Tocantins, two in Paraíso do Tocantins (10° 267 S; 48° 887 W and 411 m a.s.l.) and two in Palmas (10° 175 S; 48° 358 W and 220 m a.s.l.), with sowing performed on November 5, 2018 and January 15, 2019.

A randomized block design was used for all the experiments. The treatments were arranged in a 3 × 12 factorial scheme, with three doses of nitrogen fertilizer as topdressing at low (50 kg ha^{-1}), medium (100 kg ha^{-1}) and high N levels (150 kg ha^{-1}), to achieve minimum and maximum crop yield (Sodré et al., 2017), and 12 commercial cultivars (six GM and six non-GM). The cultivars were purchased from specialized stores in the area where the experiments were conducted, and coded from 1 to 6 (non-GM) and 7 to 12 (GM), as follows: 1.CDH (AG1051, non-GM double-cross hybrid), 2.CV (Cativerde, non-GM variety), 3.CV (Al Alvaré, non-GM variety), 4.CV (AL Bandeirante, non-GM variety), 5.CTH (BM3063, non-GM triple-cross hybrid), 6.CDH (Órion, non-GM double-cross hybrid), 7.GTH (BM3063, GM triple-cross hybrid), 8.GTH (2B655PW, GM triple-cross hybrid), 9.GSH (2M95VIP3, GM single-cross hybrid), 10.GSH (30S31VYH, GM single-cross hybrid), 11.GSH (P3862H, GM single-cross hybrid), 12.GSH (AG709, GM single-cross hybrid).

Soil analysis was performed to determine its chemical characteristics in the experimental areas. Analysis of the chemical characteristics of the soil in Palmas showed the following results: 5.9 pH $CaCl_2$; 6.8 mg dm^{-3} of P Melich; 39 mg dm^{-3} of K; 1.2 cmol$_c$ dm^{-3} of Ca; 0.5 cmol$_c$ dm^{-3} of Mg; 1.0% OM; 54% base saturation and CEC of 3.4 cmol$_c$ dm^{-3}. The results in Paraíso do Tocantins were 6.1 pH $CaCl_2$; 14.1 mg dm^{-3} of P; 54.2 mg dm^{-3} of K; 3.6 cmol$_c$ dm^{-3} of Ca; 0.8 cmol$_c$ dm^{-3} of Mg; 1.6% OM; 76.4% base saturation and CEC of 5.94 cmol$_c$ dm^{-3}.

Temperature and rainfall data were obtained weekly at the experimental sites (Figure 1).

The experimental plot contained four 5-m-long rows spaced 0.80 m apart. Ears were collected from the two center rows and those within the 0.50 m at either end were discarded.

The soil was harrowed twice, followed by furrow opening. Based on the results of soil chemical analysis, liming was not performed. The basal dressing consisted of 400 kg ha^{-1} of 4-14-8 NPK formulation. Planting was performed manually and the desired population established after 10 days.

Nitrogen topdressing was applied manually alongside the furrow when plants were at vegetative growth stage V4, using doses of 50, 100 and 150 kg ha^{-1} of N with ammonium sulfate

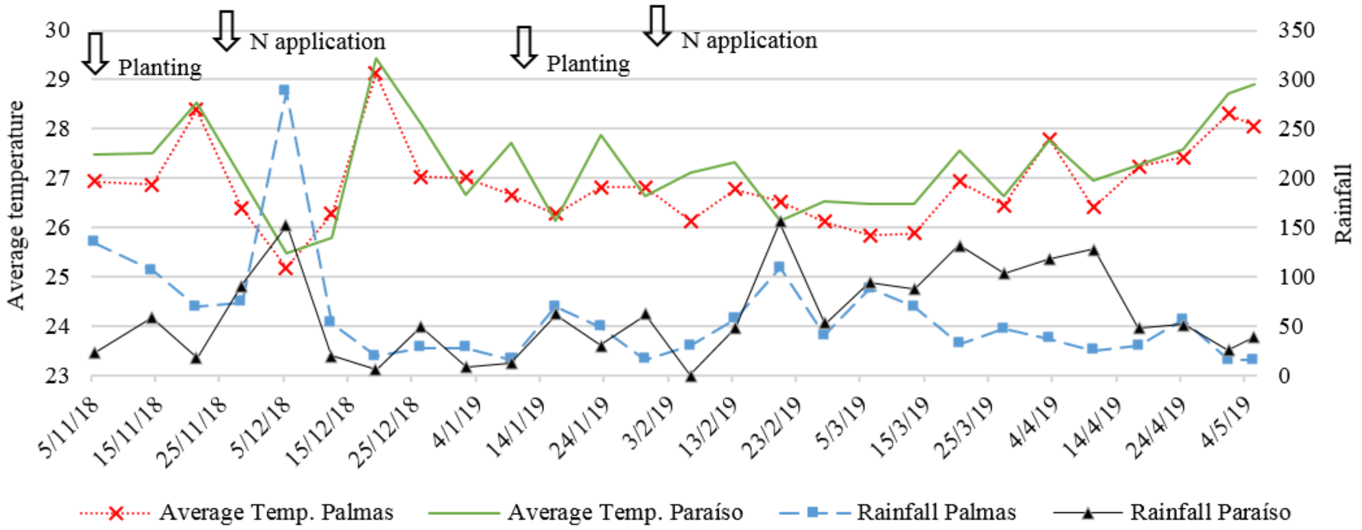

Figure 1. Weekly temperature and rainfall data in the municipality of Paraíso do Tocantins and Palmas in 2018 and 2019

(21% N and 22% S) as the source. The doses used for high and low N environments corresponded to the lowest and highest expected grain yields for corn (Santos et al., 2016).

Stage V4 is when the plant displays four fully developed leaves and the number of grains and yield potential is established. A single application of N at this growth stage is the most beneficial (Magalhães & Durães, 2006; Begnini et al., 2018).

Pest, disease and weed control were performed as described by Fancelli & Dourado Neto (2000).

The grains collected in each experiment were identified according to the N dose and cultivar used, then weighed and converted into kg ha^{-1} after correction for a 13% moisture content.

For statistical analysis, the N dose in each experiment represented a different environment. As such, combinations of the three N doses and four experiments produced 12 environments, presented in Table 1.

The yield data for each environment were submitted to individual analysis of variance (ANOVA) followed by pooled ANOVA of all the environments, using a seven-fold higher residual mean square for the latter. Next, adaptability, stability and environmental stratification were analyzed.

The methods used for adaptability and stability were in line with those described by Eberhart & Russel (1966) and Lin & Binns (1988), modified by Carneiro (1998).

According to Eberhart & Russell (1966), genotypes with a regression coefficient of one ($\beta1 = 1$) exhibit general or broad adaptability; $\beta1 > 1$ specific adaptability to favorable environments and $\beta1 < 1$ specific adaptability to unfavorable environments. An ideal genotype has a yield higher than the overall mean, regression coefficient equal to one ($\beta1 = 1$) and predictable behavior ($\sigma^2d = 0$). Based on this methodology, stability is estimated by deviation from the regression (σ^2d) or the coefficient of determination (R^2), which exhibit an inverse correlation, that is, stable genotypes have high R^2 values and low σ^2d values.

The Lin & Binns (1988) methodology is based on estimating the parameter Pi, which measures the distance from the maximum response of the genotype trait studied for each environment. Carneiro (1998) proposed improving the technique to determine the behavior of genotypes in specific environments, that is, favorable and unfavorable. With broad environmental adaptability/stability, the ideal genotype exhibits a high mean and low Pi.

Table 1. Environments produced by combinations of location, sowing time and N topdressing doses in the 2018/19 and 2019/20 growing seasons

Environments	Location	Date	kg of N ha^{-1}
1	Paraíso do Tocantins	05/11/2018	50
2		05/11/2018	100
3		05/11/2018	150
4	Palmas	05/11/2018	50
5		05/11/2018	100
6		05/11/2018	150
7	Paraíso do Tocantins	15/01/2019	50
8		15/01/2019	100
9		15/01/2019	150
10	Palmas	15/01/2019	50
11		15/01/2019	100
12		15/01/2019	150

1.CDH (AG1051, non-GM double-cross hybrid), 2.CV (Cativerde, non-GM variety), 3.CV (Al Alvaré, non-GM variety), 4.CV (AL Bandeirante, non-GM variety), 5.CTH (BM3063, non-GM triple-cross hybrid), 6.CDH (Órion, non-GM double-cross hybrid), 7.GTH (BM3063, GM triple-cross hybrid), 8.GTH (2B655PW, GM triple-cross hybrid), 9.GSH (2M95VIP3, GM single-cross hybrid), 10.GSH (30S31VYH, GM single-cross hybrid), 11.GSH (P3862H, GM single-cross hybrid), 12.GSH (AG709, GM single-cross hybrid)

Environmental clustering was performed by stratification and dissimilarity based on the algorithm proposed by Lin algorithm (1982), whereby the sum of squares for interaction between cultivars and environment pairs is estimated and the environments with nonsignificant interaction grouped.

Complex and straightforward cultivar-environment interactions were estimated as described by Cruz & Castoldi (1991) and, finally, Pearson's correlation between environment pairs was determined.

Although similar to the algorithm proposed by Lin (1982), the Cruz & Castoldi (1991) method provides an additional possibility because, in addition to grouping environments with nonsignificant C x E interaction, those with significant but predominantly simple interaction can also be clustered without changing the rank order of genotypes in relation to the locations/environments studied. Statistical analyses were performed using Genes software, version 2007.

Results and Discussion

As shown in Table 2, analysis of variance demonstrated a significant effect for cultivars, environments and cultivar-environment interaction, the last being primarily complex (CI) (Table 3) with weak correlations (R) between environments (Table 3). This indicates that cultivar behavior differed as a function of the environment, thereby justifying adaptability, stability and environmental stratification analysis.

The coefficient of variation (CV%) was 18.2, indicating adequate precision in the field experiments (Pimentel-Gomes 2009). Similar results were reported by Carvalho et al. (2013) (CV% 16.86) and Mijone et al. (2019) (CV% 19.51), who studied the adaptability and stability of corn cultivars in South Central Tocantins state and Patos de Minas in Minas Gerais state, respectively.

Analysis of the environmental indices (Table 4) according to Eberhart & Russel (1966) demonstrated that environments four, five and six (Palmas, sowing on 05/11/2018 and seven, eight and nine (Paraíso, sowing on 15/01/2019) were classified as favorable for exhibiting a higher mean value than the overall mean for the environments (positive environmental index). All the environments exhibited uniform rainfall distribution

Table 2. Summary of a pooled analysis of variance of average yield in twelve environments in Paraíso do Tocantins and Palmas

Source of variation	DF	Mean square
Block/Environment	22	2844090.3
Cultivar	11	30628449.8*
Environment	11	39205912.6*
Environment × Cultivar	121	1480638.4*
Residue	264	1121128.9
Mean kg ha^{-1}	5816	
CV%	18.2	

* Significant at $p \leq 0.05$, respectively; DF - Degrees of freedom; CV - Coefficient of variation

Table 3. Estimated simple (%SI) and complex (%CI) C x E interaction and correlation (R) between pairs of 12 environments for twelve corn cultivars based on average yield, according to the Cruz & Castoldi (1991) method and Pearson's correlation (r)

Average yield															
Pair	%SI	%CI	r	Pair	% SI	%CI	r	Pair	% SI	%CI	r	Pair	% SI	%CI	r
1 x 2	66.9	33.1	0.77	1 x 3	81.3	18.7	0.95	1 x 4	41.9	58.1	0.66	1 x 5	63.8	36.2	0.74
1 x 6	34.1	65.9	0.56	1 x 7	42.1	57.9	0.66	1 x 8	30.7	69.3	0.51	1 x 9	26.5	73.5	0.35
1 x 10	47.1	52.9	0.65	1 x 11	61.2	38.8	0.71	1 x 12	41.4	58.6	0.62	2 x 3	59.1	40.9	0.73
2 x 4	38.8	61.2	0.45	2 x 5	40.5	59.5	0.64	2 x 6	38.9	61.1	0.48	2 x 7	72.7	27.3	0.80
2 x 8	76.6	23.4	0.84	2 x 9	42.2	57.8	0.65	2 x 10	49.5	50.5	0.71	2 x 11	66.1	33.9	0.88
2 x 12	67.7	32.3	0.84	3 x 4	50.4	49.6	0.74	3 x 5	67.9	32.1	0.80	3 x 6	37.1	62.9	0.60
3 x 7	43.6	56.4	0.66	3 x 8	35.2	64.8	0.57	3 x 9	15.9	84.1	0.23	3 x 10	42.1	57.9	0.63
3 x 11	52.4	47.6	0.66	3 x 12	43.4	56.6	0.67	4 x 5	50.3	49.7	0.58	4 x 6	44.7	55.3	0.69
4 x 7	40.8	59.2	0.64	4 x 8	33.2	66.8	0.55	4 x 9	13.4	86.6	0.12	4 x 10	36.9	63.1	0.52
4 x 11	50.7	49.3	0.58	4 x 12	46.4	53.6	0.67	5 x 6	32.7	67.3	0.39	5 x 7	56.9	43.1	0.65
5 x 8	47.8	52.2	0.57	5 x 9	23.1	76.9	0.39	5 x 10	35.9	64.1	0.55	5 x 11	34.4	65.6	0.56
5 x 12	56.3	43.7	0.74	6 x 7	45.9	54.1	0.70	6 x 8	38.9	61.1	0.62	6 x 9	10.9	89.1	0.11
6 x 10	59.9	40.1	0.78	6 x 11	60.5	39.5	0.71	6 x 12	32.5	67.5	0.52	7 x 8	65.7	34.3	0.88
7 x 9	33.6	66.4	0.43	7 x 10	65.3	34.7	0.80	7 x 11	80.9	19.1	0.86	7 x 12	70.8	29.2	0.87
8 x 9	33.7	66.3	0.45	8 x 10	52.9	47.1	0.71	8 x 11	78.9	21.1	0.85	8 x 12	68.8	31.2	0.87
9 x 10	24.1	75.9	0.41	9 x 11	36.3	63.7	0.57	9 x 12	37.9	62.1	0.58	10 x 11	73.8	26.2	0.90
10 x 12	49.8	50.2	0.73	11 x 12	69.2	30.8	0.84								

1.CDH (AG1051, non-GM double-cross hybrid), 2.CV (Cativerde, non-GM variety), 3.CV (Al Alvaré, non-GM variety), 4.CV (AL Bandeirante, non-GM variety), 5.CTH (BM3063, non-GM triple-cross hybrid), 6.CDH (Órion, non-GM double-cross hybrid), 7.GTH (BM3063, GM triple-cross hybrid), 8.GTH (2B655PW, GM triple-cross hybrid), 9.GSH (2M95VIP3, GM single-cross hybrid), 10.GSH (30S31VYH, GM single-cross hybrid), 11.GSH (P3862H, GM single-cross hybrid), 12.GSH (AG709, GM single-cross hybrid)

throughout the root development period, ensuring better use of fertilizer and improved root development.

By contrast, environments one, two and three (Paraíso, sowing on 05/11/2018) and 10, 11 and 12 (Palmas, sowing on 15/01/2019) obtained a lower mean value than the overall mean and were therefore considered unfavorable (negative environmental index), probably because the large volume of rainfall in the early stage of the crop cycle (Figure 1) compromised initial plant development, which, combined with the likely leaching of basal and topdressing, had a negative effect on final yield. Additionally, low rainfall was recorded in Paraiso between 20/12/2018 and 10/01/2019, when plants were in the stage at which their yield potential is defined. Mijone et al. (2019) found that unfavorable environments may result from an inadequate climate or limited use of technology and resources.

According to Magalhães & Durães (2006), water stress can affect internode length, contributing to lowering the sugar storage capacity of stems and resulting in thinner stems, smaller plants and a smaller leaf area, which can compromise development. Additionally, soil flooding can hamper growth or even kill the plant in a matter of days.

In this respect, for each location and sowing time, the N topdressing doses used (50, 100 and 150 kg of N ha^{-1}) did not alter the classification of environments as favorable or unfavorable, which occurred predominantly as a function of the different rainfall indices at each location and sowing time.

Classifying environments is important because cultivars may respond differently to different environments, hampering cultivar selection and recommendation (Bornhofen et al., 2017; Pacheco et al., 2017; Oliveira et al., 2018; EMBRAPA, 2020). As such, estimating the magnitude and nature of cultivar x environment interaction is highly relevant, since these estimates make it possible to assess the real impact of selection and ensure a high degree of reliability in genotype recommendation for a specific location or group of environments (Capone et al., 2016; Oda et al., 2019).

Table 4. Environmental index (Ij) for average yield in 12 environments, obtained by the Eberhart & Russell (1966) method, at two sowing times in Paraíso do Tocantins and Palmas

Environment	Environmental index	
	Average kg environment	Environmental Index (Ij)
1	5093	-724.1
2	5200	-617.1
3	5146	-670.9
4	6499	682.8
5	6522	704.9
6	6550	733.1
7	6526	709.2
8	7095	1278.8
9	7372	1555.5
10	4469	-1347.5
11	4447	-1369.9
12	4882	-934.7
Overall mean	5817	

1.CDH (AG1051, non-GM double-cross hybrid), 2.CV (Cativerde, non-GM variety), 3.CV (Al Alvaré, non-GM variety), 4.CV (AL Bandeirante, non-GM variety), 5.CTH (BM3063, non-GM triple-cross hybrid), 6.CDH (Órion, non-GM double-cross hybrid), 7.GTH (BM3063, GM triple-cross hybrid), 8.GTH (2B655PW, GM triple-cross hybrid), 9.GSH (2M95VIP3, GM single-cross hybrid), 10.GSH (30S31VYH, GM single-cross hybrid), 11.GSH (P3862H, GM single-cross hybrid), 12.GSH (AG709, GM single-cross hybrid)

The adaptability and stability parameters for average yield according to the methods of Eberhart & Russell (1966) and Lin & Binns (1988) - modified by Carneiro (1988), are presented in Table 5.

Except for cultivar 1 (non-GM), all the cultivars analyzed exhibited non-significant deviation from the regression ($\sigma^2 d$) according to the Eberhart & Russell (1966) method and were therefore able to remain stable, indicating predictable behavior.

For adaptability according to the method described by Eberhart & Russel (1966), non-GM cultivars 1, 2, 3, 5 and 6 and GM cultivar 8 obtained regression coefficients lower than one ($\beta 1 < 1$), indicating adaptation to unfavorable environments, that is, with low investment in crop technology. However, in these environments, 1, 3, 5 and 6 obtained mean values were higher than the overall mean and can therefore be classified as having broad adaptability.

Table 5. Adaptability and stability parameters for average yield according to the methods of Eberhart & Russell (1966) and Lin & Binns (1988) - modified by Carneiro (1988) in 12 environments at two sowing times, in Paraíso do Tocantins and Palmas

Cultivar	Mean	Average yield					
		Ebehart & Russel			Lin & Binns		
		Environmental index	β_1	S^2d	Pi	Pi_{Fav}	Pi_{Ufav}
1	6881.91	-724.0	0.728*	894103.76*	446368.89	754178.3	138559.4
2	4378.52	-617.0	0.860*	311872.43^{ns}	5533990.35	7097350.6	3970630.1
3	5860.75	-670.9	0.849*	-2939.54^{ns}	1827078.03	2374714.5	1279441.5
4	4022.13	682.8	1.042*	83110.84^{ns}	6411373.65	7004148.0	5818599.2
5	6677.00	704.8	0.935*	-303928.98^{ns}	534311.91	746069.9	322553.9
6	6012.75	733.0	0.960*	81568.74^{ns}	1373464.89	1566187.5	1180742.1
7	6895.10	709.1	1.227*	-168046.4^{ns}	423730.93	415526.6	431935.2
8	5503.77	1278.7	0.898*	77904.61^{ns}	2625369.95	2753556.3	2497183.5
9	5539.30	1555.4	1.248*	29761.13^{ns}	2337052.47	1709295.7	2964809.2
10	5345.97	-1347.5	1.213*	31731.21^{ns}	2715263.98	2200714.0	3229813.9
11	6191.80	-1369.9	1.012^{ns}	-45029.08^{ns}	1418001.21	1817182.6	1018819.8
12	6491.02	-934.7	1.023*	145376.85^{ns}	860616.10	1254980.9	466857.2
Overall mean	5817						

Source: research data; Cultivar:1-AG1051; 2-Cativerde; 3-AL Alvaré; 4-AL Bandeirante; 5-BM3063; 6-Órion; 7-BM3063; 8-2B655PW; 9-2M95VIP3; 10-30S31VYH; 11-P3862H; 12-AG709. β1 - Regression coefficient; S^2d - Deviation from the regression; Pi - Superiority index; Pi_{Fav} - Adapted to favorable environments; Pi_{Ufav} - Adapted to unfavorable environments; *, ns - Significant at 0.05 probability and not significant, respectively, according to the t-test for (β1) and F-test for (S^2d)

Based on the Lin & Binns (1988) method modified by Carneiro (1988), cultivars 1 and 5 also exhibited a low Pi_{Ufav} value, indicating adaptable/stable behavior in unfavorable environments.

In studies by Santos et al. (2020) and Dias et al. (2021), cultivars 1 and 6 and cultivar 1, respectively, were also classified as adapted to unfavorable environments and nonresponsive to increased N.

As reported by Afférri et al. (2020), the environmental adaptability of cultivars is influenced by factors such as soil, location, growing season, sowing time, management practices and technologies used, and indicates their ability to make the best use of environmental stimuli (Mastrodomenico et al., 2018).

In general, most of the cultivars adapted to these environments were non-GM, which may be because these crops are designed for environments with fewer resources and less investment in technology, making them potentially more tolerant of adverse conditions.

Non-GM cultivar 4 and GM cultivars 7, 9, 10 and 12 obtained regression coefficients greater than one ($\beta 1 > 1$), demonstrating adaptation to favorable environments that typically receive higher investments in technology. The favorable environments in the present study were not exposed to adverse weather conditions. Of these cultivars, only the mean values of 7 and 12 were higher than the overall mean.

The Lin & Binns (1988) method modified by Carneiro (1998) also revealed low Pi_{Fav} values for cultivars 7 and 10. In favorable environments, most of the cultivars were the result of greater investment in biotechnology (GM), which likely occurred because these environments are not affected by unstable climates, thereby allowing them to express their genetic potential.

The regression coefficient of cultivar 11 (GM) was one ($\beta 1 = 1$), with a mean value above the overall mean and predictable behavior, thus making it ideal, that is, adapted to both favorable and unfavorable environments and predictable, according to the Eberhart & Russel (1966) method.

The Lin & Binns (1988) parametric method modified by Carneiro (1998) showed lower Pi values for cultivars 1, 5, and 7, demonstrating general adaptability.

The fact that different cultivars were found to exhibit general adaptability can be explained by the different approaches to the data in each methodology, demonstrating the potential of each cultivar.

According to Carvalho et al. (2014), highly adaptable cultivars are a good choice in markets where the materials available are not adapted to the specific conditions, which may be relevant for Tocantins state. Chandel et al. (2019) found that the development of highly adaptable cultivars is one of the objectives of breeding programs.

The environment groups obtained using the Lin algorithm (1982) method are shown in Table 6.

Six groups of similar environments were obtained, with group 1 containing 11 environments and only environment 9 excluded. As such, group 1 consisted of different N doses, sowing times and locations.

The remaining groups all contained environment 9 (Palmas, 15/01/2019) combined with either environment 2 (Group II), 11 (Group III), 12 (Group IV), 5 (Group V) or 10 (Group 6). Of these, environments 10, 11 and 12 are in the same location (Palmas, sowing 15/01/2019), but received different N doses.

Silva et al. (2015) reported that alleles responsible for genetically controlling N efficiency are expressed according to the degree of N availability. As such, the difference between cultivars in different environments may have occurred due to

Table 6. Yield-based grouping of the 12 environments according to the method proposed by Lin (1982), at two sowing times, in Paraíso do Tocantins and Palmas

Average yield	
Group	Environment
I	1; 3; 5; 2; 11; 12; 10; 7; 8; 6; 4
II	9; 2
III	9; 11
IV	9; 12
V	9; 5
VI	9; 10

1.CDH (AG1051, non-GM double-cross hybrid), 2.CV (Cativerde, non-GM variety), 3.CV (Al Alvaré, non-GM variety), 4.CV (AL Bandeirante, non-GM variety), 5.CTH (BM3063, non-GM triple-cross hybrid), 6.CDH (Órion, non-GM double-cross hybrid), 7.GTH (BM3063, GM triple-cross hybrid), 8.GTH (2B655PW, GM triple-cross hybrid), 9.GSH (2M95VIP3, GM single-cross hybrid), 10.GSH (30S31VYH, GM single-cross hybrid), 11.GSH (P3862H, GM single-cross hybrid), 12.GSH (AG709, GM single-cross hybrid)

N availability, resulting in the expression or not of alleles that favor N absorption and use for plant growth.

Thus, in general, the climate factors (rainfall and temperature) and N doses used (50, 100 and 150 kg ha^{-1}) at different sowing times and locations did not cause significant changes in the environments. In order to optimize human and financial resources in breeding programs, the number of environments can be reduced from two growing seasons to one and two locations to one, with less nitrogen fertilization (50 kg de N ha^{-1}). This finding is corroborated by Afférri et al. (2020), who evaluated the adaptability and stability of corn genotypes, and by Matta et al. (2020) in research with sunflowers.

Conclusions

1. In general, genetically modified (GM) cultivars were better adapted to favorable environments.

2. Most of the non-GM cultivars were adapted to unfavorable environments.

3. All the environments exhibited similar behavior regardless of location, seeding time and the N dose used, demonstrating that fewer environments can be used in future breeding research.

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