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Adaptability and stability of maize hybrids using the Eberhart and Russell and AMMI models in subtropical environments

Adaptabilidade e estabilidade de híbridos de milho pelas metodologias de Eberhart e Russell e AMMI em ambientes subtropicais

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ABSTRACT

Brazil boasts a vast variety of environmental conditions conducive to maize cultivation. Given the various maize hybrids available in the Brazilian market, properly selecting and positioning different genetic materials are critical for successful grain production. Thus, this study aimed to determine the adaptability and stability of different maize hybrids, comparing the Eberhart and Russell and AMMI models, to guide the positioning of these maize hybrids in subtropical regions. A randomized block experimental design with six hybrids and three replicates was used. The experimental environments were defined by combinations of factors such as location, sowing time, fungicide management and irrigation, resulting in 12 distinct environments. Notably, the two models largely agree. For instance, the AG 9025 PRO3 hybrid showed a high yield during early sowing under favorable conditions, whereas the AS 1730 PRO3 and DKB 230 PRO3 hybrids had good yields even under unfavorable conditions. The main limitation of the Eberhart and Russell model is its limited ability to interpret stability, classifying hybrids only as having high or low predictability, limiting the detailed interpretation of stability. Conversely, the AMMI model offers a more detailed analysis of stability, allowing the interpretation of hybrid stability within a broader set and presenting information graphically, which facilitates understanding and enables a more comprehensive and accurate analysis for the appropriate positioning of maize hybrids.

Index Terms: Irrigation; fungicide management; yield; *Zea mays* L.

RESUMO

O Brasil apresenta uma diversidade de condições ambientais propícias para o cultivo de milho. Considerando a quantidade de híbridos de milho disponíveis no mercado brasileiro, a seleção e o posicionamento precisos dos materiais genéticos são fundamentais para o êxito na produção. Este estudo tem como objetivo determinar a adaptabilidade e estabilidade de diferentes híbridos de milho, comparando as metodologias de Eberhart e Russell e AMMI, para orientar o posicionamento desses híbridos em regiões subtropicais. Utilizou-se um delineamento experimental em blocos ao acaso com seis híbridos e três repetições. Os ambientes experimentais foram definidos por combinações de fatores como local, época de semeadura, manejo com fungicida e irrigação, resultando em 12 ambientes distintos. Os resultados demonstram que as metodologias avaliadas corroboram parcialmente entre si. O *híbrido AG 9025 PRO3* mostrou-se altamente produtivo em semeaduras precoces em ambientes favoráveis. Em contraste, os híbridos AS 1730 PRO3 e DKB 230 PRO3 apresentaram bom desempenho produtivo mesmo em condições desfavoráveis. A principal limitação do modelo Eberhart e Russell é a sua capacidade limitada de interpretar a estabilidade, classificando os híbridos apenas como de alta ou baixa previsibilidade, o que limita a interpretação detalhada da estabilidade. Por outro lado, o modelo AMMI oferece uma análise mais detalhada da estabilidade, permitindo interpretar a estabilidade dos *híbridos* dentro de um conjunto mais amplo e apresentar informações de forma gráfica, o que facilita a compreensão e possibilita uma análise mais abrangente e precisa para o posicionamento adequado de híbridos de milho.

Termos para indexação: Irrigação; manejo de fungicida; produtividade; *Zea mays* L.

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Introduction

Maize (*Zea mays* L.) production is a widely spread agricultural activity throughout Brazil, highlighting the remarkable ability of different genetic materials to adapt to the varied environmental conditions of the country. Furthermore, maize is essential to the Brazilian agro-industrial complex, with domestic consumption representing roughly 60% of the 131 million tons produced in the 2022/2023 season (Companhia Nacional de Abastecimento - Conab, 2023). Brazil is the third-largest maize producer in the world, following the United States and China, which produced 348 and 277 million tons, respectively. The global average maize yield in 2022 was approximately 5.7 tons per hectare, with the United States achieving 10.8 tons per hectare and Brazil 6.1 tons per hectare (Foof and Agriculture Organization of the United Nations - FAOSTAT, 2024; Conab, 2023). Globally, maize production is growing at a rate of 1.6% per year, while in Brazil, it ranges at 1.7–4% per year. Nonetheless, despite these growth levels, we are predicted to only reach 67% of the projected production expectation to meet future food demand by 2050 (Ray et al., 2013).

The subtropical region of Brazil stands out as an area of significant importance for the country's production, with roughly 19% of the country's total production (Conab, 2023). Despite this potential, the mean yield in the subtropical region during the 2022/2023 harvest was only 6.2 tons per hectare, significantly below the crop's potential maximum of over 20 tons per hectare under subtropical conditions (Coelho et al., 2022). Hence, this discrepancy presents a significant challenge in maximizing the agronomic performance of maize hybrids.

The Brazilian market offers a wide range of maize cultivars, varying from 98 to 479, as observed from the 2007/2008 to 2021/2022 harvests (Pereira Filho & Borghi, 2020). In light of this, the strategic positioning of maize cultivars is crucial in optimizing grain production. Therefore, the effective use of adaptability and stability methods is key to enhancing yield and improving the quality of the production system with the goal of long-term sustainability.

Several statistical methods are used to assess the adaptability and stability of hybrids, which can be based on analysis of variance, linear regression, nonlinear regression, multivariate analysis, and nonparametric statistics (Bastos et al., 2007). Rezende et al. (2021) reviewed the scientific literature on adaptability and stability methods in maize and soybean, identifying 21 distinct methods in 113 studies published between 1970 and 2017. Among the most widely used methods are Eberhart and Russell (linear regression) and AMMI (multivariate analysis). The method proposed by Eberhart and Russell employs simple linear regression analysis to measure the response of each genotype under different environmental conditions (Eberhart & Russell, 1966). Although this approach is valued for its ease of interpretation of results, its effectiveness may be compromised by the need for the data to meet the assumptions of a linear regression analysis and by the dependence on an environmental index based on the mean of the genotypes evaluated (Carvalho et al., 2016).

In contrast, the AMMI method combines analysis of variance with singular value decomposition to evaluate genotype-environment interactions (Gauch, 1992). Using biplot graphs, which combine the variances of the additive effects of genotypes and environments with the multiplicative effects of the G x E interaction, AMMI allows a detailed interpretation of the results through principal component analysis. The clarity of the graphical interpretation may be limited when the number of genotypes and environments is high, which may make interpretation difficult (Carvalho et al., 2016).

Comparison between methods is essential, since different models offer different perspectives on the adaptability and stability of hybrids. Cargnelutti Filho et al. (2007) compared seven analysis methods and concluded that the Eberhart and Russell method is the preferred method, while Yamamoto et al. (2021) suggested the combined use of MHPRVG and GGE-Biplot to select more promising genotypes in Central Brazil.

Given this context, this study aimed to determine the adaptability and stability of different maize hybrids, comparing the Eberhart and Russell and AMMI models, to guide the positioning of these maize hybrids in subtropical regions.

Material and Methods

The experiments were conducted at three locations during the 2020/2021 crop year in the subtropical region of Rio Grande do Sul State (southern Brazil): São Vicente do Sul (SVS; 29º42'27"S, 54º41'34"W; 129 m altitude) and Santa Maria (SM; 29º43'28"S, 53º43'41"W; 95 m altitude) with Utisol (or Red Dystrophic Argisol) and Frederico Westphalen (FW; 27º23'42"S, 53º25'43"W, 480 m altitude) with Oxisol (or Red Dystrophic Latosol according to the Brazilian Soil Classification System) (Figure 1). The climate in the study area is humid subtropical with hot summers (Cfa) according to the Köppen classification (Alvares et al., 2013). Twelve environments (E) were established across these locations. Several variables impacted the yield of maize hybrids, including sowing time, fungicide use, soil type, soil fertility, and the center pivot irrigation system.

The 12 experiments utilized a randomized block design with six maize hybrids, each replicated thrice. The chosen hybrids were representative of the growing regions and included six varieties from six commercial companies. They were as follows: AG 9025 PRO3, AS 1730 PRO3, P 3016 VYHR, MG 300 PW, DKB 230 PRO3, and SYN Feroz VIP3. For the twelve experiments, a total of 216 plots were evaluated. Each plot consisted of six rows spaced 0.50 m apart and five meters long, yielding an area of 15 m^2 per plot.

The winter cultivation that preceded the maize was the intercropping of black oat (*Avena strigosa* L.) and forage radish (*Raphanus sativus* L.). After desiccating the cover crops, a base fertilization was applied to achieve a target yield of 12 t ha^{-1} of grains using a seeder and, subsequently the experiment was manually seeded in order to increase experimental precision, with a density of 70,000 plants ha^{-1}. Nitrogen fertilization was applied at the V4 and V6 stages with urea (45% nitrogen). Other crop treatments, such as herbicide and insecticide applications, adhered to technical guidelines for maize production in Rio Grande do Sul State (Da Rosa, Emygdio, & Bispo, 2017).

Table 1 lists the experimental areas, sowing date, associated management, mean minimum and maximum air temperatures, and rainfall during the experiments. Irrigation experiments used a center pivot according to water demand. In fungicide experiments, two foliar applications were conducted following technical recommendations for the crop: one at the V8 stage and another at the VT stage. The fungicides propiconazole and picoxystrobin + cyproconazole were used to control major fungal diseases in maize crops.

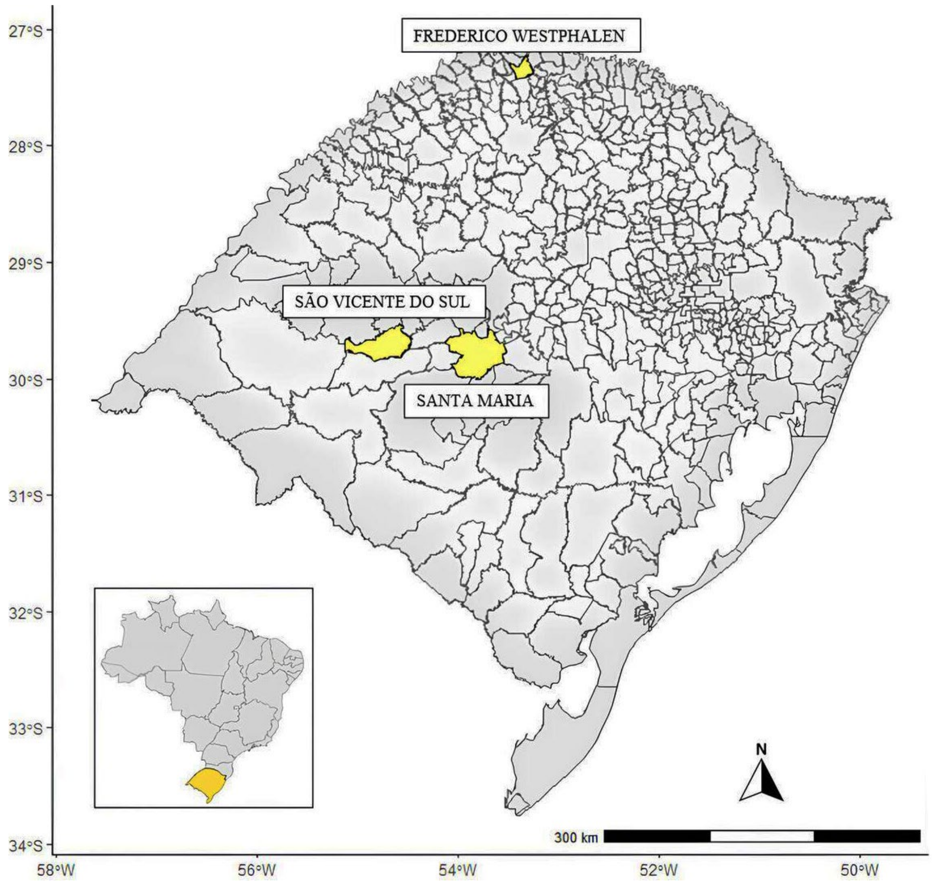

Figure 1: Geographical representation of the three locations where experiments were conducted with six maize genotypes subjected to different management practices during the 2020/2021 crop year in Rio Grande do Sul (southern Brazil).

Table 1: Description of the 12 environments where experiments were carried out with six maize genotypes subjected to different management practices in the 2020/2021 crop year in Rio Grande do Sul (southern Brazil).

Environment	Location	Sowing date	Min. temp. (°C)	Max. temp. (ºC)	Rainfall (mm)	Irrigation management	Fungicide management
E1	SVS	22/09	15.9	29.9	460	Rainfed	No
E2	SVS	22/09	15.9	29.9	675	Irrigated	No
E3	SVS	06/11	16.9	30.5	608	Irrigated	No
E4	SM	14/09	14.9	28.1	482	Rainfed	No
E5	SM	23/10	16.5	29.3	450	Rainfed	No
E6	FW	18/09	17.3	30.3	532	Rainfed	No
E7	SVS	22/09	15.9	29.9	460	Rainfed	Yes
E8	SVS	22/09	15.9	29.9	675	Irrigated	Yes
E9	SVS	06/11	16.9	30.5	608	Irrigated	Yes
E10	SM	14/09	14.9	28.1	482	Rainfed	Yes
E11	SM	23/10	16.5	29.3	450	Rainfed	Yes
E12	FW	18/09	17.3	30.3	532	Rainfed	Yes

FW: Frederico Westphalen; SM: Santa Maria; SVS: *São Vicente do Sul.* Meteorological data to characterize each location were obtained from automatic meteorological stations up to 600 m from the experiments. The rainfall volume was increased according to the volume of irrigation.

Rainfall volume included irrigation volume. Grain yield (t ha^{-1}), ascertained from an 8 m^2 area within each plot, consisted of the four central rows, each four meters long. Harvesting occurred when grain moisture hit 20%, which was adjusted to 13% to determine grain yield. Variance homogeneity amongst environments was examined through individual variance analyses for each trial. A joint variance analysis followed for the experimental group, assuming that the ratio between the maximum mean square residual and minimum mean square residual was <7. The joint analysis was conducted with Equation 1:

$$Y_{ijk} = \mu + G_i + A_j + GA_{ij} + \frac{B}{A_{jk}} + \varepsilon_{ijk} \quad (1)$$

Where μ is the overall mean, G_i is the effect of the i^{th} genotype (i = 1, 2, ..., g), A_j is the effect of the j^{th} environment (j = 1, 2, ..., e), GA_{ij} is the effect of the interaction between the i^{th} genotype and the j^{th} environment, B/A_{jk} is the effect of the k^{th} block within the j^{th} environment (k = 1, 2, ..., r), and $\mathcal{E}_{ijk}$ is the random error. Subsequently, adaptability and stability analyses were conducted using the model of Eberhart and Russell (1966) (Equation 2):

$$Y_{ij} = \mu_i + \beta_i l_j + \delta_{ij} + \varepsilon_{ijk} \quad (2)$$

Where Y_{ij} is the mean of genotype i in environment j, μ_1 is the overall mean of genotype i, β_i is the linear regression coefficient that quantifies the response of genotype i to environmental changes, l_j is the environmental index, δ_{ij} is the regression deviation for genotype i in environment j, and ε_{ij} is the standard error associated with the mean. The additive main effect and multiplicative interaction (AMMI) model is implemented according to Gauch (1992) and using Equation 3:

$$Y_{ij} = \mu + g_i + e_j + \sum_{k=1}^{n} \lambda_k \gamma_{ik} \alpha_{jk} + \rho_{jk} + \varepsilon_{ij} \quad (3)$$

Where the mean yield of genotype i in environment j is represented by Y_{ij}, μ is the general mean, g_i is the genotype effect, e_j is the effect of environment, λ_k is the singular value of the principal component's k^{th} axis, γ_{ik} is the i^{th} element of genotypes' k^{th} eigenvector, and α_{jk} is the j^{th} element of the environment's k^{th} eigenvector. The additional error to be eliminated from the genotype (G) x E interaction analysis is represented by ρ_{jk}, and $\mathcal{E}_{ij}$ is for the experimental error (Duarte & Vencovsky, 1999).

All analyses were performed using the Metan package and ggplot2 in the R software (v. 4.3.1) (Olivoto & Lúcio, 2020; Wickham, 2016; R Core Team, 2023).

Results and Discussion

Six environments had total rainfall greater than 500 mm during the experimental period, while another six had less than 500 mm (Table 1). This variability influences the selection of hybrids to match specific environmental conditions. Grassini, Yang and Cassman (2009) stipulated that a hybrid's maximum agronomic performance is governed by solar radiation and temperature but limited by water availability.

Water needs for maize crops fluctuate throughout their cycle and are influenced by factors such as air temperature, humidity, soil type, and the productive potential of the maize hybrid. Overall, water requirements range from 500 to 800 mm per cycle, reaching up to 7 mm per day during critical periods (e.g., grain filling) (Bergamaschi & Matzenauer, 2014). Considering only water, the mean maize yield is 19.3 kg ha^{-1} mm^{-1} (Grassini et al., 2011). Rainfall during the experiments varied by over 200 mm, from 450 mm in E5 and E11 to 675 mm in E2 and E8. This variation affects the production potential of a given environment and influences the choice of the best hybrid for cultivation, since water stress is the main cause of productivity losses. Nevertheless, the genetic variability of hybrids under irrigation and water stress conditions allows us to identify those with better performance in rainfed environments (Mohanapriya et al., 2023).

The mean minimum air temperature during the experiments ranged from 14.9 °C in E4 and E10 to 17.3 °C in E6 and E12. The mean maximum air temperature spanned from 28.1 to 30.5 °C in E4 and E10 and E3 and E9, respectively. Notably, the optimal mean air temperature for maize crop development is around 25 °C (Bergamaschi & Matzenauer, 2014). Elevated air temperatures enhance photosynthetic rates and hasten leaf area expansion during the vegetative phase, thereby affecting the duration of phenological events and potentially reducing yield (Bergamaschi & Matzenauer, 2014). In regions with cooler nighttime temperatures, plant respiration slows, conserving energy and promoting plant development (Niu et al., 2021). Consequently, maize hybrids are more likely to achieve their production potential under these conditions.

The residue's largest to smallest mean squares ratio was 5.59, indicating uniform residual variances as per Gomes' criteria (1990), allowing for joint analysis (Table 2). The grain yield's joint variance analysis showed a significant cultivar-environment interaction in the experiments. This uncovered different hybrid behaviors in the environments, suggesting hybrid selection can be effectively guided by an adaptability and stability analysis.

The correlation between genotype and environment is evident in the yield analysis (Figure 2).

Table 2: Joint variance analysis and significance of causes of variation for grain yield (t ha^{-1}), mean values, experimental coefficients of variation, and the ratio between the highest and lowest residual mean squares for the environments (RMS^{+}/RMS^{-}).

Causes of variation	DF	SQ	RMS
Blocks/environments	24	24.11	1.00
Hybrids	5	164.83	32.96*
Environment	11	210.91	19.17*
GEI	55	187.58	3.41*
Residual	120	79.49	0.66
Mean			8.98
CV (%)			9.05
RMS^{+}/RMS^{-}			5.59

DF: degree of freedom; RSS: residual sum of squares; RMS: residual mean square; GEI: genotype × environment interaction; CV: coefficient of variation; *Significant at 5% probability by the F test.

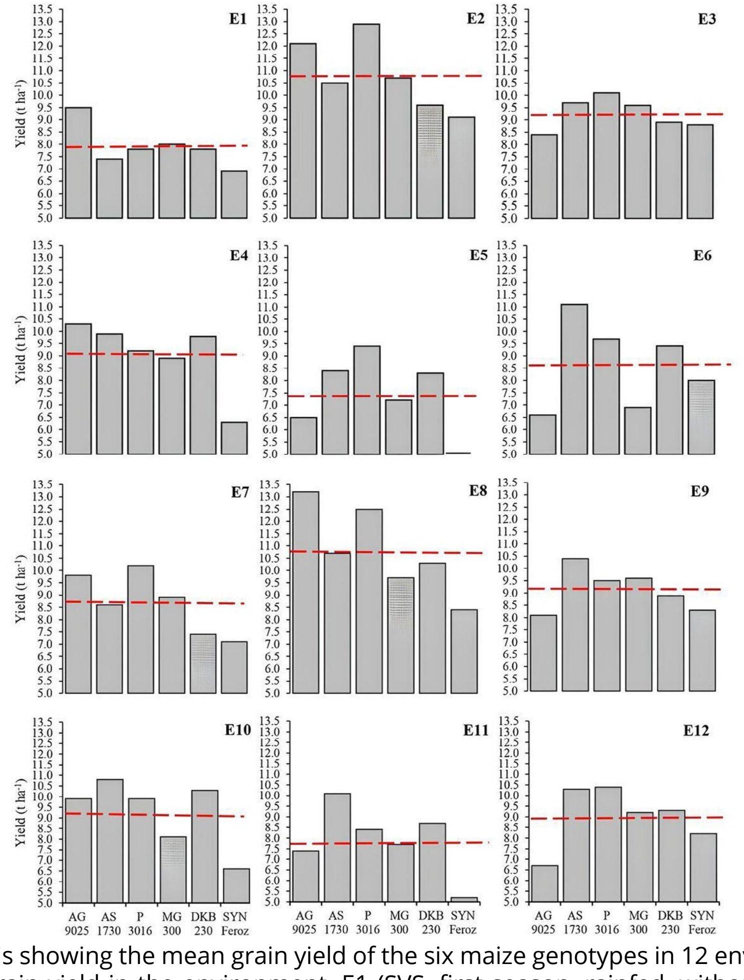

Figure 2: Descriptive analysis showing the mean grain yield of the six maize genotypes in 12 environments. The red dashed line represents the mean grain yield in the environment. E1 (SVS, first season, rainfed, without fungicide application); E2 (SVS, first season, irrigated, without fungicide application); E3 (SVS, second season, irrigated, without fungicide application); E4 (SM, first season, rainfed, without fungicide application); E5 (SM, second season, rainfed, without fungicide application); E6 (FW, first season, rainfed, without fungicide application); E7 (SVS, first season, rainfed, with fungicide application); E8 (SVS, first season, irrigated, with fungicide application); E9 (SVS, second season, irrigated, with fungicide application); E10 (SM, first season, rainfed, with fungicide application); E11 (SM, second season, rainfed, with fungicide application); E12 (FW, first season, rainfed, with fungicide application). Note: SVS: São Vicente do Sul; SM: Santa Maria; FW: Frederico Westphalen.

The agronomic performance of hybrids generally varies according to the environmental conditions. For instance, the hybrid AG 9025 PRO3 exhibited optimal yield in E1 but had the worst performance in E12, demonstrating an environmental impact on its performance. Remarkably, only two hybrids—AG 9025 PRO3 and P 3016 VYHR—achieved a yield over 12 t ha^{-1} in two distinct areas, E2 and E8, both with irrigation and sown early, and this aligns with their geographical distribution in areas with greater investments (Ben et al., 2019). However, nutrient and water use efficiency was high for these materials since the other hybrids, even under the same environmental conditions and presenting a similar cycle, did not exceed the yield barrier designed in the fertilizer planning (yield of 12 t ha^{-1}).

Figure 2 also allows one to classify each environment as favorable or unfavorable by comparing the mean yield to the overall mean, which sits at 9 t ha^{-1}. Although the yield did not reach the expectation of 12 t ha^{-1}, it was higher than the state average, which was 5.4 t ha^{-1} (Conab, 2023). Thus, an environment with a mean yield higher than this overall mean was deemed favorable (Carvalho et al., 2013), and the favorable environments were E2, E3, E4, E8, E9, E10, and E12, while E1, E5, E6, E7, and E11 were considered unfavorable.

As observed in favorable areas, ideal conditions for growing maize include irrigation via the center pivot (E2, E3, E8, and E9) and early sowing in September (E4, E10, and E12). However, not all environments sown in September proved favorable (E1, E6, and E7). The application of foliar fungicide was beneficial in E6 and E12. In E6, where no fungicide was applied, the mean yield was 8.6 t ha^{-1}, in contrast to 9 t ha^{-1} in E12, where fungicide was applied. Fungicides reduce the severity and incidence of fungal diseases in maize (Penney et al., 2021). Moreover, using fungicides to manage maize crops impacts the relationships between maize plant traits (Follmann et al., 2023), potentially significantly increasing maize grain yield (Wise et al., 2019). In fact, evidence has shown that disease severity is negatively correlated with grain yield (Da Silva et al., 2014).

E1 and E7 experienced water deficits during crucial stages, including budding and grain filling, and received only 460 mm of rainfall. Moreover, geographically proximate areas with center pivot irrigation (E2 and E8) were deemed advantageous. Conversely, those sown in late October in a rainfed system (E5 and E11), with only 450 mm of rainfall, were considered unfavorable for maize cultivation were unfavorable.

Access to water through irrigation can boost yield and reduce potential loss by up to 40% (Ben et al., 2019). Furthermore, early sowings utilize radiation and air temperature more effectively as they align the flowering and grain-filling period with peak solar radiation in subtropical regions (Bolzan et al., 2024). Maize crops are weather-responsive, and factors such as rainfall and air temperature impact their yield potential (Evans & Fischer, 1999). For Coelho et al. (2022), the delay in the sowing season from early to late spring may reduce the productive potential of maize by up to 24%.

The adaptability analysis, evaluated by the ß1 parameter using the Eberhart and Russell model, indicated that the AG 9025 PRO3 hybrid adapted well to an improved environment, yielding a mean of 9 t ha^{-1} (Table 3). Conversely, the AS 1730 PRO3 and DKB 230 PRO3 hybrids adapted well to unfavorable environments with mean yields of 9.83 and 9 t ha^{-1}, respectively. Moreover, the hybrids P 3016 VYHR, MG 300 PWU, and SYN Feroz VIP3 were found to be highly adaptable to varying environmental conditions, yielding means of 9.99, 8.71, and 7.31 t ha^{-1}, respectively.

Table 3: Estimates of adaptability and stability generated by the Eberhart and Russell (1966) and AMMI models for grain yield in 6 maize hybrids grown in 12 environments of Rio Grande do Sul State (southern Brazil).

Hybrids	Mean (t ha^{-1})	Eberhart and Russell			AMMI		
		ß1	S^2d	R^2	Axis	PC (%)	∑ PC (%)
AG 9025 PRO3	9.00	1.617*	1.848*	0.596	1	56.1	56.1
AS 1730 PRO3	9.83	0.653*	0.673*	0.358	2	24.1	80.2
P 3016 VYHR	9.99	1.268^{ns}	0.284*	0.788	3	11.1	91.3
MG 300 PWU	8.71	0.887^{ns}	0.281*	0.647	4	6.4	97.7
DKB 230 PRO3	9.00	0.589*	0.283*	0.446	5	2.3	100
SYN Feroz VIP3	7.31	0.985^{ns}	0.672*	0.560			

PC: principal component. ß1: regression coefficient. When ß1* is significantly different from 1 according to the t-test, there is a 5% probability of error. Adaptability is assessed in the following ways: ß1^{ns} indicates a hybrid's general or broad adaptability, ß1>1* suggests a hybrid's adaptability to favorable environments, and ß1<1* points to a hybrid's adaptability to unfavorable environments. The variance of the regression deviation is represented by S^2d. If S^2d* significantly deviates from zero, tested by the F test, there is a 5% probability of error. Stability is evaluated using S^2d values: S^2d^{ns} signifies a stable hybrid with high predictability, while S^2d>0* represents a hybrid with low stability. The coefficient of determination is represented by R^2.

The stability analysis, gauged by regression deviations (S^2d) using the Eberhart and Russell model, revealed that the hybrids did not maintain stability under the evaluated conditions. This suggests that changes under environmental conditions can significantly influence their response. The simplified approach of the model, which classifies hybrids as having high or low predictability, may be a limitation to this study, as it does not allow one to closely assess the intensity of instability among hybrids. Furthermore, the low R^2 values indicate that the model explains only a small part of the variability observed in the data. This suggests that other alternative methods of analyzing adaptability and stability, which offer a more precise decomposition of the genotype x environment interaction, may be better suited for a comprehensive assessment (Cruz et al., 1989).

The AMMI analysis demonstrates that the main axis (PC1) accounted for 56.1% of the variation in the $SQ_{G \times E}$. This is followed by PC2 and PC3, which accounted for 24.1 and 11.1%, respectively, thereby cumulating over 90% of the total variance (Table 3). The AMMI1 and AMMI2 (Figure 3) suggest that maize hybrids or environments with points nearest to the biplot origin are deemed more stable (Duarte & Vencovsky, 1999). Conversely, scattered points represent genotype-environment interactions, leading to specific adaptations.

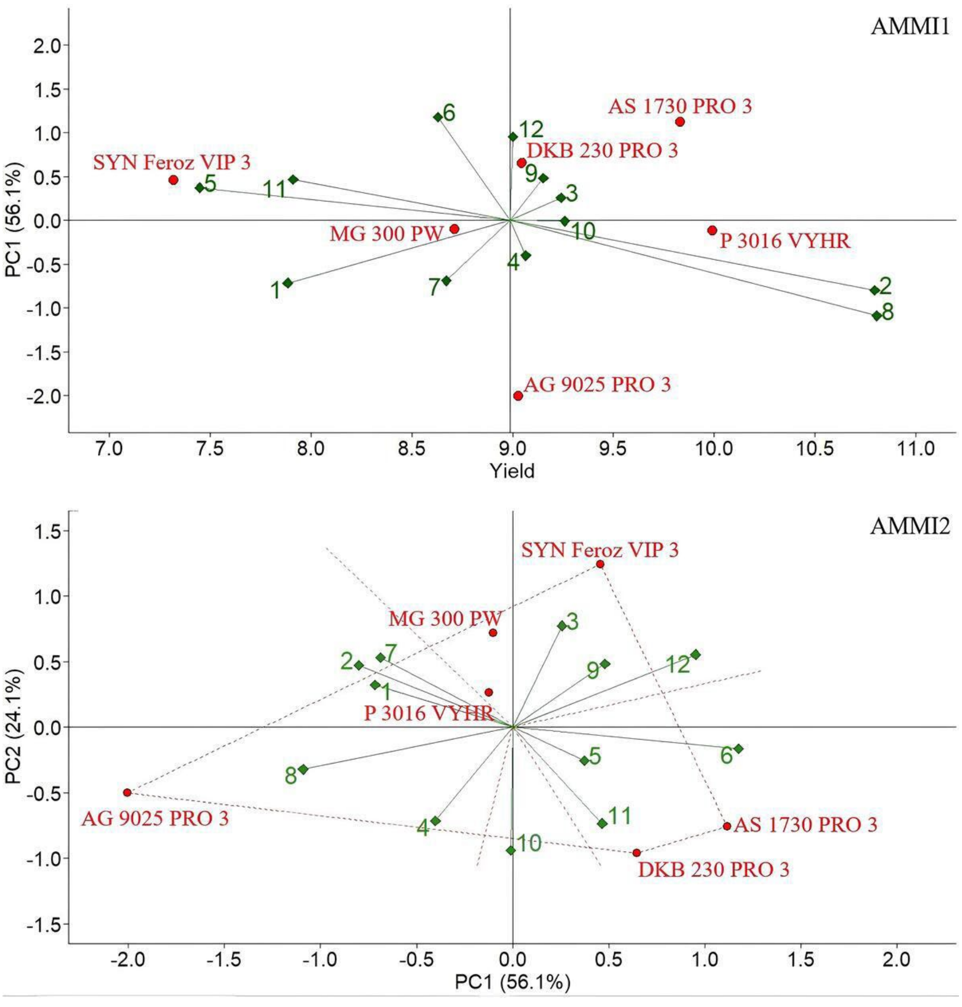

Figure 3: Biplot analysis, AMMI 1 (yield vs PC1) and AMMI2 (PC1 vs PC2) of 6 maize hybrids (in red) in 12 environments (in green). E1 (SVS, first season, rainfed, without fungicide application); E2 (SVS, first season, irrigated, without fungicide application); E3 (SVS, second season, irrigated, without fungicide application); E4 (SM, first season, rainfed, without fungicide application); E5 (SM, second season, rainfed, without fungicide application); E6 (FW, first season, rainfed, without fungicide application); E7 (SVS, first season, rainfed, with fungicide application); E8 (SVS, first season, irrigated, with fungicide application); E9 (SVS, second season, irrigated, with fungicide application); E10 (SM, first season, rainfed, with fungicide application); E11 (SM, second season, rainfed, with fungicide application); E12 (FW, first season, rainfed, with fungicide application). Note: SVS: São Vicente do Sul; SM: Santa Maria; FW: Frederico Westphalen.

In the AMMI1 analysis (Figure 3), the hybrids MG 300 PWU and P 3016 VYHR, explained by PC1, are the most stable genotypes that contributed minimally to the interaction. As a result, these hybrids are considered stable given their minor contribution to the G×E interaction. Hybrids AS 1730 PRO3 and P3016 VYHR show the highest mean yield, as indicated by their position in the right quadrants of the biplot graph. Hybrids AS 1730 PRO3 and DKB 230 PRO3 are specifically adaptable to E3, E6, and E12, evident in the biplot's top-right quadrant. The AG 9025 PRO3 hybrid, located in the lower-right quadrant, and SYN Feroz VIP3, located in the top-left quadrant, exhibit specific adaptability for E2, E4, E8, and E10 and E5, E6, E11, respectively. The hybrids MG 300 PWU and P 3016 VYHR, located near the center pivot, have wide adaptability to varying environmental conditions. Nonetheless, hybrid P 3016 VYHR produces an above-mean yield, contrasting hybrid MG 300 PWU's below-mean yield.

In the AMMI1 analysis (Figure 3), the hybrids MG 300 PWU and P 3016 VYHR, explained by PC1, are the most stable genotypes that contributed minimally to the interaction. As a result, these hybrids are considered stable given their minor contribution to the G×E interaction. Hybrids AS 1730 PRO3 and P3016 VYHR show the highest mean yield, as indicated by their position in the right quadrants of the biplot graph. Hybrids AS 1730 PRO3 and DKB 230 PRO3 are specifically adaptable to E3, E6, and E12, evident in the biplot's top-right quadrant. The AG 9025 PRO3 hybrid, located in the lower-right quadrant, and SYN Feroz VIP3, located in the top-left quadrant, exhibit specific adaptability for E2, E4, E8, and E10 and E5, E6, E11, respectively. The hybrids MG 300 PWU and P 3016 VYHR, located near the center pivot, have wide adaptability to varying environmental conditions. Nonetheless, hybrid P 3016 VYHR produces an above-mean yield, contrasting hybrid MG 300 PWU's below-mean yield.

The AMMI2 analysis (PC1 vs. PC2), which accounts for over 80% of the genotype-environment interaction with PC1 and PC2, validates the findings in AMMI1. It demonstrates that hybrid P 3016 VYHR, which contributed the least to the interaction, is the most stable hybrid for the studied locations. Furthermore, this hybrid has a yield above the mean, making it an ideal hybrid with broad adaptability, predictability, and high yield.

Moreover, the AMMI2 graph revealed four distinct macro-environments, although one macro-environment, comprised solely of E10, lacks hybrids with specific adaptability. The first macro-environment, consisting of E3, E9, and E12, exhibits favorable conditions, including rainfall over 530 mm and above-mean minimum (>17 °C) and maximum (>30 °C) temperatures. These conditions fostered high yields from SYN Feroz VIP3 and MG 300 PW hybrids whose mean yields exceeded their overall means. These results indicate that the irrigation system effectively compensated for the delay in the sowing season, since E3 and E9 were sown on November 6. These findings corroborate Fabris et al. (2023), who demonstrated that, although sowing delay can negatively impact maize productivity, adequate irrigation management can mitigate these effects.

The second macro-environment, with E1, E2, E4, E7, and E8, was planted early in September, indicating that sowing time greatly influences the performance of AG 9025 PRO3 hybrids. Sowing maize early is therefore recommended to allow hybrids to fully express their yield potential, particularly in subtropical climates with higher radiation. The hybrid's mean yield in these environments was higher than its overall and macro-environment mean, supporting Eberhart and Russell's finding that the hybrid responds well to enhanced environmental conditions, thereby standing out as a good option for cultivation in low investment conditions or in late sowing due to its productive robustness in unfavorable environments.

The third macro-environment (E5, E6, and E11) were deemed unfavorable conditions, yet the AS 1730 PRO3 and DKB 230 PRO3 hybrids remained productive. Despite these difficult conditions, these hybrids achieved yields surpassing the environment's overall mean, corroborating Eberhart and Russell's identification of these hybrids' adaptability to unfavorable areas.

Both models (i.e., Eberhart and Russell and the AMMI) are frequently employed to evaluate maize hybrids by measuring adaptability and stability to increase maize yield. While both techniques produce comparable results, the AMMI model's graphical visualization offers a more comprehensive analysis, expediting the evaluation of various hybrids in different scenarios. The graphical visualization provided by the AMMI model is one of its advantages over the Eberhart and Russell method, providing detailed observations of specific adaptability between hybrids and environments. In addition, the AMMI model enables more in-depth analyses of the degree of stability of hybrids to be made, unlike Eberhart and Russell, which limits the classification of predictability to high or low, making a more comprehensive interpretation difficult.

This visual approach aids in identifying the most stable and adaptable hybrids for various locations, leading to informed decisions crucial to maximizing maize grain yield in subtropical regions. Decisions such as selecting the most suitable hybrid for particular environmental conditions are fundamental and require analysis of all information such as sowing time, irrigation, pest management, and soil attributes, among others. These data should be used to assess the productive potential of the environment and select the most fitting hybrid to meet grain yield expectations.

Conclusions

The Eberhart and Russell and AMMI models confirmed that the AG 9025 PRO3 hybrid exhibits high yields in early sowings in favorable environments. Conversely, the AS 1730 PRO3 and DKB 230 PRO3 hybrids performed satisfactorily even under unfavorable conditions. For the AMMI model, the P3016 VYHR hybrid showed commercial potential due to its large grain yield, regional adaptability, and predictable response, diverging in parts from the Eberhart and Russell analysis that determines low predictability.

Author Contribution

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