

## Analysis of Yield Stability of Sugarcane Varieties and Representativeness of Test Locations Using AMMI and HA-GGE Biplots: Postprint

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**Date:** 2017-11-07T00:00:00+00:00

### Abstract

Conducting genotype-by-environment interaction analysis on sugarcane regional trial data facilitates a comprehensive understanding of the high-yielding ability of tested varieties and the representativeness of trial sites, and holds significant importance for the promotion of superior new varieties and their regional distribution. This study comprehensively utilized the AMMI model and HA-GGE biplot to analyze yield stability and high-yielding ability of cane yield and sugar yield data from 11 varieties and 13 trial sites in the 10th national sugarcane regional trial of 2014, and to evaluate the representativeness and discriminating ability of the trial sites. The results indicated that highly significant differences existed in both cane yield and sugar yield among different varieties and trial sites, and that highly significant interaction effects were present between varieties and trial sites. ‘Funong 40’ exhibited the best overall performance, being a variety with high yield, good high-yielding ability, and strong stability in both cane yield and sugar yield; ‘Yunzhe 08-2060’ showed slightly lower yield than ‘Funong 40’, but possessed stronger stability in cane yield and sugar yield than ‘Funong 40’; compared with the control variety ‘ROC22’, ‘Yuegan 43’, ‘Yuegan 46’, and ‘Mintang 02-205’ had higher cane yield and sugar yield with moderate stability; ‘Funong 40’, ‘Yuegan 43’, ‘Yuegan 46’, and ‘Yunzhe 08-2060’ all demonstrated strong adaptability and could be promoted and applied in suitable sugarcane-growing regions. The integrated AMMI and HA-GGE biplot analysis results indicated that Suixi in Guangdong, Kaiyuan in Yunnan, and Fuzhou in Fujian possessed high site discriminating ability and trial site representativeness. Therefore, the comprehensive application of AMMI and HA-GGE biplots can more accurately and intuitively evaluate the high-yielding ability, stability, and adaptability of each variety, as well as the discriminating ability and representativeness of each trial site. This study can provide valuable theoretical reference for the identification and promotion of new sugarcane varieties.

## Full Text

# Analysis of Yield Stability and Test Site Representativeness of Sugarcane Varieties Using Combined AMMI and HA-GGE Biplot Models

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## Abstract

Knowledge of yield stability of sugarcane varieties and representativeness of test sites during national regional trials is critical for rational regional distribution and guiding sugarcane breeding. Additive main effects and multiplicative interaction (AMMI) and heritability-adjusted GGE (HA-GGE) biplot models are two widely used statistical methods for analyzing crop variety trial data. Using experimental data from regional trials, the interactions between crop genotype and environment can be analyzed to determine the yield potential of tested varieties and the representativeness of test sites. To assess the representativeness and discrimination ability of 13 test locations in the sugarcane variety trial, the AMMI model was used in combination with HA-GGE biplot to analyze cane and sugar yields of 11 sugarcane varieties planted at national regional trial sites across China. The results showed that cane and sugar yields differed significantly among varieties and test sites, with significant genotype  $\times$  environment interaction effects.

The 'FN40' sugarcane variety exhibited the best overall performance, combining high yield, good productivity, and high stability for both cane and sugar yields. The yield of 'YZ08-2060' was slightly lower than that of 'FN40', while its stability for both cane and sugar yields was slightly higher than that of 'FN40'. Compared with the control variety 'ROC22', 'YG43', 'YG46', and 'MT02-205' showed higher cane and sugar yields but lower stability. 'FN40', 'YG43', 'YG46', and 'YZ08-2060' all demonstrated strong adaptability and were recommended for cultivation in suitable planting areas. Further results indicated that three test locations—Suixi in Guangdong Province, Kaiyuan in Yunnan Province, and Fuzhou in Fujian Province—had higher discrimination ability and better representativeness based on comprehensive analysis using AMMI and HA-GGE biplot models. Two sugarcane varieties, 'FN40' and 'YZ08-2060', both with high yield and good stability, were recommended for commercial production across all sugarcane planting areas in China. In conclusion, the combined use of AMMI and GGE biplot models provided more accurate assessment of the productivity, stability, and adaptability of sugarcane varieties and was also highly reliable for demonstrating the discrimination ability and representativeness of test sites. This study provides a valuable reference base for the identification and promotion of new sugarcane varieties.

**Keywords:** Sugarcane; Regional trial; AMMI model; HA-GGE biplot; Cane yield; Sugar yield; Stability; Representativeness

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## Introduction

Crop variety regional trials (referred to as regional trials) are conducted across different ecological regions by selecting sites that represent various agricultural production environments—including climate, soil, temperature, humidity, and light conditions—to evaluate varieties for yield potential, stability, adaptability, resistance, quality, and other agronomic traits, as well as to assess the representativeness of test locations. An ideal regional trial should not only distinguish genetic differences among crop varieties and identify superior varieties but also determine the optimal adaptation regions for each tested variety. Through scientifically sound regional trials, new crop varieties suitable for national or regional cultivation can be continuously introduced in a timely manner, helping to avoid problems associated with variety monoculture. In crop regional trials, different test sites have varying climatic and soil conditions, leading to different performance levels of each variety across sites, which reflects the principle that crop traits are determined by both genotype and environment. Accurate evaluation of genotype  $\times$  environment ( $G \times E$ ) interactions is key to properly assessing variety stability and adaptability. In recent years, scholars have proposed various mathematical analysis methods, including linear analysis, nonlinear analysis, and principal component analysis, but these have limitations in analyzing “variety  $\times$  environment” interactions and fail to capture them accurately. This study aims to address this deficiency through the combined application of AMMI and GGE biplot models.

The AMMI model has been widely applied to analyze  $G \times E$  interactions in multi-site, multi-variety trials for crops such as proso millet (*Panicum miliaceum*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), rapeseed (*Brassica campestris*), and sugarcane (*Saccharum officinarum*). This model integrates analysis of variance with principal component analysis, separating several multiplicative terms from the interaction component of the additive model to improve estimation accuracy, and uses biplots and interaction effect values to analyze stability, adaptability, and  $G \times E$  interactions.

The GGE biplot is a new method for studying genotype  $\times$  environment interactions and evaluating crop variety yield stability and test site representativeness. This model serves as an excellent analytical tool for multi-year, multi-location regional trials, revealing complex interaction relationships among different factors. It has been widely used to process yield and quality data. The HA-GGE biplot is a heritability-adjusted version of the GGE biplot and represents an effective method for analyzing genotype  $\times$  environment interaction patterns, identifying variety ecological zones, and evaluating test sites. It assesses the idealness of test sites based on their representativeness of target environments and

their ability to discriminate genetic differences among genotypes. Currently, Luo et al. have applied HA-GGE biplot analysis to sugarcane variety trials for environmental evaluation and multi-location variety deployment.

Both AMMI and HA-GGE biplot models have individual limitations. For example, the AMMI model focuses primarily on genotype  $\times$  environment interaction effects and provides limited comprehensive evaluation of genotypes from the perspective of variety selection and promotion. This model relies on two-way data and tends to select varieties with stable high or stable low yields, potentially overlooking high-yielding but less stable varieties. Since it is not a true biplot, its application has certain limitations. The AMMI model is suitable for variety  $\times$  environment interaction analysis, while the HA-GGE biplot is more appropriate for environmental evaluation. The integrated use of AMMI and HA-GGE biplot models combines their respective strengths, allowing for comparative and comprehensive analysis of results. This approach can identify high-yielding but less stable varieties for application in suitable regions, improving the scientific accuracy of regional trial data analysis and providing a foundation for selecting superior varieties for multi-location deployment.

This study comprehensively applied AMMI and HA-GGE biplot models to analyze the genotype  $\times$  environment interaction patterns of sugarcane varieties in the 10th national round of regional trials in 2014, aiming to comprehensively evaluate variety stability and test site representativeness to provide a more scientific theoretical basis for the utilization and promotion of new sugarcane varieties.

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## Materials and Methods

**1.1 Experimental Materials** The experimental data were obtained from the 2014 new-planting season of the 10th national sugarcane variety regional trial, involving 11 test varieties coded as follows: ‘ROC22’ (G1, control), ‘FN07-2020’ (G2), ‘FN07-3206’ (G3), ‘FN40’ (G4), ‘GZ07-538’ (G5), ‘LC07-500’ (G6), ‘MT02-505’ (G7), ‘YG43’ (G8), ‘YG46’ (G9), ‘YR07-1433’ (G10), and ‘YZ08-2060’ (G11). The trial was conducted at 13 test sites: 4 in Guangxi, 4 in Yunnan, 2 in Guangdong, 1 in Hainan, and 2 in Fujian. Detailed information for each test site is presented in .

**1.2 Experimental Design** Test varieties were arranged in a randomized complete block design with four rows per plot and three replications. Each plot was 8 m long with 1.1 m row spacing, resulting in a plot area of 35.2 m<sup>2</sup>. Planting occurred from late February to early March with a seeding rate of 105,000 buds per hectare. Standard cultural practices including intertillage, earthing up, fertilization, irrigation/drainage, and pest control were performed. Yield traits were investigated before harvest, and sugar content analysis was conducted monthly from November to March of the following year. Yield measurements were taken

by weighing the middle row of each plot [17,29]. The following formulas were used to calculate relevant indices:

$$\text{Unit area effective stem number (stems} \cdot \text{hm}^{-2}) = \frac{\text{Sample effective stem number (stems)}}{\text{Sample area (m}^2)} \times 666.7 \times 15 \quad (1)$$

$$\text{Cane yield (t} \cdot \text{hm}^{-2}) = \frac{\text{Sample yield (kg)}}{\text{Sample effective stem number (stems)}} \times \frac{\text{Unit area effective stem number (stems} \cdot \text{hm}^{-2})}{1000}$$

$$\text{Sugar yield (t} \cdot \text{hm}^{-2}) = \text{Cane yield (t} \cdot \text{hm}^{-2}) \times \text{Sucrose content (\%)} \quad (3)$$

**1.3.1 AMMI Model** DPS V.14.10 software was used for statistical analysis of trait means and standard deviations [28] and for analysis of variance. Based on significant genotype  $\times$  environment interaction effects, stability analysis was performed according to the AMMI model, with the mathematical model expressed as:

$$Y_{ge} = \mu + \alpha_g + \beta_e + \sum_{n=1}^N \lambda_n \gamma_{gn} \delta_{en} + \rho_{ge}$$

Where  $Y_{ge}$  is the yield of genotype  $g$  in environment  $e$ ,  $\mu$  is the overall mean,  $\alpha_g$  is the genotype deviation,  $\beta_e$  is the environment deviation,  $\lambda_n$  is the eigenvalue of the  $n$ th interaction principal component axis (IPCA),  $\gamma_{gn}$  is the genotype score for the  $n$ th IPCA,  $\delta_{en}$  is the environment score for the  $n$ th IPCA,  $N$  is the total number of IPCA axes, and  $\rho_{ge}$  is the residual [15-16]. Significant IPCA axes were used to evaluate genotype stability based on the distance from the origin in multi-dimensional space, denoted as  $D_i$ . For varieties, stability is inversely proportional to  $D_i$  (smaller  $D_i$  indicates better stability), while for test sites, discrimination ability is directly proportional to  $D_i$  (larger  $D_i$  indicates higher discrimination). The  $D_i$  value based on significant principal components can accurately determine sugarcane variety stability for cane yield.

**1.3.2 HA-GGE Biplot** GGEbiplot software was used for HA-GGE biplot analysis [22]. Regional trial yield data were organized into a two-way table of varieties  $\times$  locations, where each value represented the phenotypic value ( $Y_{ger}$ ) of the corresponding variety at the corresponding test site. According to the linear statistical model:

$$Y_{ge} = \mu + \beta_e + \lambda_1 \gamma_{g1} \delta_{e1} + \lambda_2 \gamma_{g2} \delta_{e2} + \varepsilon_{ge}$$

Where  $\lambda_1$  is the eigenvalue of the first principal component,  $\gamma_{g1}$  is the genotype eigenvector score, and  $\delta_{e1}$  is the environment eigenvector score. The terms  $\lambda_1\gamma_{g1}$  and  $\lambda_1\delta_{e1}$  are defined as the first GGE principal component scores (PCA1 or PC1) for genotype  $g$  and environment  $e$ , respectively. In HA-GGE biplot, test environment discrimination is evaluated using the square root of heritability approximated by the vector length, while representativeness is evaluated using the genetic correlation coefficient ( $r$ ) approximated by the cosine of the angle between the environment vector and the average environment axis [22]. The H-scaled GGE biplot weights test sites by the square root of their heritability, giving higher heritability sites greater influence in variety evaluation. Vector length represents discrimination ability (positively correlated with length), and the angle between environment vectors and the average environment axis represents representativeness (inversely correlated with angle). Variety icons projected onto the average environment axis with perpendicular foot points further in the positive direction indicate better yield performance, while shorter perpendicular lines indicate greater stability.

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## Results

**2.1.1 Cane Yield** Combined ANOVA results ( ) revealed highly significant differences in cane yield among genotypes (G) and environments (E), with highly significant genotype  $\times$  environment interaction effects. The G $\times$ E interaction sum of squares accounted for 30.88% of the total sum of squares, indicating substantial environmental influence on cane yield and differential performance of the same variety across environments. Genotype variation accounted for 16.83% of the total sum of squares, while location variation accounted for 52.29%. Although location variation was substantially higher than genotype variation and represented the major portion of total variation, the genotype  $\times$  location interaction variation was 1.84 times the genotype variation, demonstrating that interaction effects are crucial for proper variety evaluation. Significance tests for interaction principal component axes (PCA) showed that the first four multiplicative terms were highly significant ( $P < 0.01$ ), with PCA5 and PCA6 also significant ( $P < 0.05$ ), collectively explaining 93.92% of the interaction sum of squares.

**2.1.2 Sugar Yield** Combined ANOVA results for sugar yield ( ) showed that genotype  $\times$  environment interaction, genotype, and environment explained 35.83%, 10.39%, and 53.77% of mean yield variation, respectively, all reaching highly significant levels. Environmental variation was substantially higher than genotype variation, representing the major portion of total variation, but the genotype  $\times$  environment interaction variation was 3.45 times the genotype variation. Clearly, genotype  $\times$  environment interaction analysis is also essential for proper variety evaluation in sugar yield. Significance tests for PCA showed that PCA1 through PCA5 were all highly significant ( $P < 0.01$ ),

explaining 32.68%, 24.45%, 17.11%, 9.93%, and 6.39% of  $G \times E$  sum of squares, respectively, and collectively accounting for 90.56% of the interaction sum of squares.

**2.2.1 AMMI Analysis of Cane Yield Stability** Mean cane yields of different varieties varied across test sites. Analysis results ( ) showed variety ranking by mean cane yield from highest to lowest as: ‘FN40’, ‘YZ08-2060’, ‘ROC22’, ‘YG43’, ‘YG46’, ‘MT02-505’, ‘FN07-2020’, ‘FN07-3206’, ‘YR07-1433’, ‘LC07-500’, ‘GZ07-538’. Variety stability ranking from strongest to weakest was: ‘ROC22’, ‘YZ08-2060’, ‘GZ07-538’, ‘FN07-3206’, ‘YG46’, ‘LC07-500’, ‘FN40’, ‘MT02-505’, ‘YR07-1433’, ‘FN07-2020’, ‘YG43’. Varieties with both high cane yield and strong stability included ‘YZ08-2060’, ‘ROC22’, ‘FN40’, and ‘YG46’, while those with high yield but weak stability included ‘MT02-505’, ‘FN07-2020’, and ‘YG43’.

Test site discrimination ability ranking from highest to lowest was: E9 (Lingao, Hainan), E1 (Fuzhou, Fujian), E3 (Suixi, Guangdong), E11 (Kaiyuan, Yunnan), E4 (Zhanjiang, Guangdong), and E10 (Baoshan, Yunnan). Sites with poor discrimination ability were E5 (Baise, Guangxi), E6 (Hechi, Guangxi), E12 (Lincang, Yunnan), and E2 (Zhangzhou, Fujian).

**2.2.2 AMMI Analysis of Sugar Yield** As shown in , variety ranking by mean sugar yield from highest to lowest was: ‘FN40’, ‘YZ08-2060’, ‘ROC22’, ‘YG43’, ‘MT02-505’, ‘YG46’, ‘FN07-2020’, ‘FN07-3206’, ‘GZ07-538’, ‘LC07-500’, ‘YR07-1433’. Variety stability ranking from strongest to weakest was: ‘MT02-505’, ‘YZ08-2060’, ‘ROC22’, ‘FN40’, ‘FN07-3206’, ‘LC07-500’, ‘YG43’, ‘GZ07-538’, ‘FN07-2020’, ‘YG46’, ‘YR07-1433’. Varieties with both high sugar yield and strong stability included ‘MT02-505’, ‘YZ08-2060’, ‘FN40’, and ‘ROC22’, while those with high yield but weak stability included ‘YG43’, ‘YG46’, and ‘FN07-2020’.

For sugar yield, test sites with high discrimination ability included E1 (Fuzhou, Fujian), E3 (Suixi, Guangdong), E4 (Zhanjiang, Guangdong), E10 (Baoshan, Yunnan), E5 (Baise, Guangxi), and E11 (Kaiyuan, Yunnan), while E6 (Hechi, Guangxi), E2 (Zhangzhou, Fujian), and E12 (Lincang, Yunnan) showed low discrimination ability.

**2.3.1 Cane Yield Adaptability** In variety adaptability analysis, connecting the outermost variety icons forms a polygon containing all variety icons. Perpendicular lines drawn from the biplot origin to each polygon side divide the polygon into sectors, with test environments within each sector forming an environment group. The variety at the polygon vertex in each sector performs best in the test environments within that sector.

[Figure 1: see original paper]A presents adaptability analysis for cane yield. The polygon was divided into five sectors, with all 13 test sites located in the first

sector containing four test varieties. 'FN40' performed best across all test sites, while 'ROC22', 'YG43', and 'YZ08-2060' also showed strong adaptability.

**2.3.2 Sugar Yield Adaptability** [Figure 1: see original paper]B shows variety adaptability analysis for sugar yield. In this biplot, 13 test sites were distributed across sectors 1, 2, and 3. 'ROC22', 'MT02-505', and 'YG43' showed strong adaptability in Zhanjiang, Guangdong (E4), Baise, Guangxi (E5), Hechi, Guangxi (E6), Laibin, Guangxi (E7), and Liuzhou, Guangxi (E8). 'FN40' and 'YZ08-2060' demonstrated strong adaptability in Fuzhou, Fujian (E1), Suixi, Guangdong (E3), Kaiyuan, Yunnan (E11), and Lincang, Yunnan (E12). 'YG46' exhibited strong adaptability in Zhangzhou, Fujian (E2), Lingao, Hainan (E9), Baoshan, Yunnan (E10), and Dehong, Yunnan (E13).

**2.4.1 Cane Yield Stability** As shown in [Figure 2: see original paper]A, the first principal component explained 41.2% of G+GE variation, and the second principal component explained 17.9%, with the HA-GGE biplot accounting for 59.1% of genotype and GE interaction information. For cane yield, 'FN40' showed the best yield performance, followed by 'YZ08-2060' and 'ROC22'. 'YG43', 'YG46', and 'MT02-505' yielded above the overall trial mean but below the control 'ROC22', while 'FN07-3206', 'FN07-2020', 'LC07-500', 'GZ07-538', and 'YR07-1433' had lower yields, consistent with the mean yield rankings in . 'YZ08-2060', 'FN40', and 'YG43' combined high cane yield with strong stability; 'ROC22', 'MT02-505', and 'YG46' had high yield with medium stability; 'FN07-3206', 'GZ07-538', and 'LC07-500' had low yield with medium stability; and 'FN07-2020' and 'YR07-1433' had low yield with weak stability.

**2.4.2 Sugar Yield Stability** [Figure 2: see original paper]B shows that the first principal component explained 28% of G+GE variation and the second principal component explained 22%, with the HA-GGE biplot accounting for 50% of genotype and GE interaction information. For sugar yield, 'YZ08-2060', 'FN40', 'YG46', and 'YG43' exceeded the control 'ROC22', while 'MT02-505' exceeded the trial mean but was below 'ROC22'. 'FN07-3206', 'GZ07-538', 'FN07-2020', 'LC07-500', and 'YR07-1433' had lower sugar yields than 'ROC22', with yield trends generally consistent with . 'FN40', 'YZ08-2060', and 'ROC22' combined high sugar yield with strong stability; 'MT02-505' and 'YG43' had high yield with medium stability; 'YG46' had high yield with weak stability; and 'FN07-3206', 'GZ07-538', 'FN07-2020', 'LC07-500', and 'YR07-1433' had low yields with weak stability.

**2.5.1 Test Site Discrimination and Representativeness for Cane Yield** [Figure 3: see original paper]A evaluates test environment discrimination and representativeness for cane yield. Test environment discrimination ability ranked as: Suixi, Guangdong (E3) > Lingao, Hainan (E9) > Hechi, Guangxi (E6) > Lincang, Yunnan (E12) > Baise, Guangxi (E5) > Zhangzhou, Fujian

(E2) > Liuzhou, Guangxi (E8) > Kaiyuan, Yunnan (E11) > Dehong, Yunnan (E13) > Baoshan, Yunnan (E10) > Laibin, Guangxi (E7) > Fuzhou, Fujian (E1) > Zhanjiang, Guangdong (E4). Representativeness ranked as: Lincang, Yunnan (E12) > Kaiyuan, Yunnan (E11) > Fuzhou, Fujian (E1) > Laibin, Guangxi (E7) > Liuzhou, Guangxi (E8) > Zhangzhou, Fujian (E2) > Baise, Guangxi (E5) > Hechi, Guangxi (E6) > Lingao, Hainan (E9) > Zhanjiang, Guangdong (E4) > Dehong, Yunnan (E13) > Suixi, Guangdong (E3) > Baoshan, Yunnan (E10). Overall, Lincang, Yunnan showed the best representativeness and good discrimination ability.

### 2.5.2 Test Site Discrimination and Representativeness for Sugar Yield

[Figure 3: see original paper]B analyzes test environment discrimination and representativeness for sugar yield. Discrimination ability ranked as: Baise, Guangxi (E5) > Liuzhou, Guangxi (E8) > Lingao, Hainan (E9) > Suixi, Guangdong (E3) > Lincang, Yunnan (E12) > Dehong, Yunnan (E13) > Kaiyuan, Yunnan (E11) > Baoshan, Yunnan (E10) > Hechi, Guangxi (E6) > Zhangzhou, Fujian (E2) > Laibin, Guangxi (E7) > Fuzhou, Fujian (E1) > Zhanjiang, Guangdong (E4). Representativeness ranked as: Suixi, Guangdong (E3) > Kaiyuan, Yunnan (E11) > Fuzhou, Fujian (E1) > Lincang, Yunnan (E12) > Zhangzhou, Fujian (E2) > Zhanjiang, Guangdong (E4) > Dehong, Yunnan (E13) > Lingao, Hainan (E9) > Liuzhou, Guangxi (E8) > Hechi, Guangxi (E6) > Baise, Guangxi (E5) > Baoshan, Yunnan (E10) > Laibin, Guangxi (E7). Overall, Suixi, Guangdong showed the best representativeness and good discrimination ability.

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## Discussion and Conclusion

Due to genotype  $\times$  environment interactions, environmental changes significantly affect crop growth and yield. Therefore, analyzing regional trial data requires consideration of not only crop genotype but also genotype  $\times$  environment interaction effects, as simple two-dimensional data expression cannot clearly represent these relationships. If analytical methods for regional trial data are not objective and accurate, even well-designed trials with excellent field management cannot fully realize their potential to guide variety promotion and deployment. This study simultaneously applied AMMI and HA-GGE biplot methods to analyze data from the 2014 national sugarcane variety regional trial. The two complementary models produced largely consistent results regarding variety yield potential, stability, and test site representativeness, suggesting that the conclusions are scientifically sound and objective.

The two primary objectives of sugarcane breeding are high yield and high sugar content, but these traits are often contradictory, with varieties typically being either high-yielding with low sugar content or low-yielding with high sugar content. To balance sucrose content and cane yield, sugar yield is used as the ultimate criterion for evaluating sugarcane varieties. This study analyzed yield potential and stability from both cane yield and sugar yield perspectives. The

AMMI model focuses on analyzing variety  $\times$  site interaction effects and stability. For cane yield, 'ROC22' showed the best stability, followed by 'YZ08-2060'; for sugar yield, 'MT02-505' showed the best stability, followed by 'YZ08-2060'. The HA-GGE biplot focuses on variety adaptability and yield potential. For cane yield, 'FN40' demonstrated broad adaptability, while 'ROC22', 'YG43', and 'YZ08-2060' showed strong adaptability. For sugar yield, 'ROC22', 'MT02-505', and 'YG43' showed strong adaptability in five test sites including Zhanjiang, Guangdong (E4), while 'FN40' and 'YZ08-2060' showed strong adaptability in four test sites including Fuzhou, Fujian (E1). For cane yield, 'FN40' showed the best yield potential, followed by 'YZ08-2060'; for sugar yield, 'YZ08-2060', 'FN40', 'YG46', and 'YG43' showed higher sugar yields. Integrating results from both models, 'FN40' achieved the highest cane and sugar yields, followed by 'YZ08-2060'. Both 'YZ08-2060' and 'FN40' showed strong stability for both cane and sugar yields. 'YG43' and 'YG46' demonstrated above-average performance for both cane and sugar yields, representing high-yielding varieties with medium stability. Overall, 'FN40', 'YG43', 'YG46', and 'YZ08-2060' all showed strong adaptability and are recommended for extension in suitable sugarcane regions.

Under different ecological conditions, the ideal sugarcane variety combines high yield, stable yield, and broad adaptability, but such varieties are rare in practice. Low-yielding varieties, even with strong stability, cannot be widely deployed. Thus, variety stability is meaningful only when combined with high yield. The integrated use of AMMI and HA-GGE biplot models enables convenient and rapid analysis of variety yield potential, adaptability, and stability, providing a reliable basis for scientific variety deployment.

Proper test site selection is crucial for crop breeding. For cane yield, Suixi, Guangdong showed the strongest discrimination ability, followed by Lingao, Hainan and Hechi, Guangxi, while Lincang, Yunnan showed the strongest representativeness, followed by Kaiyuan, Yunnan and Fuzhou, Fujian. For sugar yield, Baise, Guangxi showed the strongest discrimination ability, followed by Liuzhou, Guangxi and Lingao, Hainan, while Suixi, Guangdong, Kaiyuan, Yunnan, Fuzhou, Fujian, and Lincang, Yunnan ranked highest in representativeness. The differences in discrimination ability and representativeness between cane yield and sugar yield analyses likely reflect that different traits are controlled by different genes, which interact with the same environment to varying degrees, or that the same genes are affected differently by the same environment, resulting in varying discrimination ability for the same site across traits controlled by different genes.

It should be emphasized that in practical agricultural production and breeding, few varieties combine high yield with strong stability, and the probability of perfect combination is low. Only high-yielding, stable varieties are suitable for extensive cultivation. The two varieties identified in this study, 'FN40' and 'YZ08-2060', combine high cane and sugar yields with strong stability, representing high-yielding and stable sugarcane varieties with high potential value

in production. They are recommended for widespread application as broadly adapted varieties.

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### Acknowledgments

This study utilized data from the 2014 new-planting season of the 10th national variety regional trial. We express our sincere gratitude to all participating institutions and personnel.

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