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Vijeta Gupta
CCS HAU Regional Research
Station, Uchani, Karnal, Haryana,
India

Application of AMMI, GGE and stability models in sugarcane breeding

Vijeta Gupta

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Abstract

Sugarcane (*Saccharum* spp. complex) is one of the world's most important commercial crops, contributing significantly to sugar production, bioenergy generation, and rural livelihoods. However, the expansion of sugarcane cultivation into diverse agro-climatic regions has increased the influence of genotype $\times$ environment interaction (GEI), which complicates the identification and selection of stable, high-yielding cultivars. Stability and adaptability analyses have therefore become essential components of modern sugarcane breeding programs. This review examines the application of three widely used statistical approaches—Eberhart and Russell regression model, Additive Main Effects and Multiplicative Interaction (AMMI) analysis, and Genotype plus Genotype $\times$ Environment (GGE) biplot analysis—for evaluating GEI and identifying stable sugarcane genotypes across multiple environments. The review synthesizes findings from studies conducted in India and other sugarcane-growing countries, highlighting the effectiveness of these models in detecting stable, high-yielding, and stress-tolerant genotypes under varying environmental conditions, including drought, salinity, and climatic variability. AMMI and GGE biplot analyses have proven particularly useful in visualizing genotype performance, defining mega-environments, and optimizing testing locations, while the Eberhart and Russell model remains valuable for assessing adaptability and stability through regression parameters. The review also discusses key challenges associated with stability analyses, including unbalanced datasets, climate variability, ratoon crop effects, lack of environmental covariates, and conflicting genotype rankings among different models. Integrating advanced GEI models with genomic tools, environmental characterization, and precision breeding approaches will enhance selection efficiency and support the development of resilient sugarcane varieties for sustainable production under changing climatic conditions.

Keywords: Sugarcane, Genotype $\times$ Environment Interaction (GEI), AMMI Analysis, GGE Biplot

Introduction

Sugarcane (*Saccharum* spp. complex) is one of the most important commercial crops of the world and a principal source of sugar, bio-ethanol, jaggery and several agro-industrial by-products. It contributes significantly to food security, energy sustainability and rural livelihoods, particularly in tropical and subtropical regions (Kaahwa, 2023) ^[12]. The ever-increasing demand for sugar and bio-energy, driven by rapid population growth, industrialization and changing consumption patterns, has necessitated the expansion of sugarcane cultivation into new and marginal agro-ecological regions that were previously considered unsuitable for its production (Singh and Nath, 2020) ^[29].

Expansion of sugarcane cultivation into diverse environments exposes the crop to a wide range of climatic and edaphic stresses such as high temperature, moisture deficit, waterlogging, salinity and variable soil fertility (Verma *et al.*, 2023) ^[33]. These environmental fluctuations significantly influence cane yield, juice quality traits and overall productivity. To ensure sustainable sugarcane production under such variable conditions, it is imperative to develop and identify genotypes that are not only high yielding but also stable across environments. Stability refers to the ability of a genotype to perform consistently over a wide range of environments, whereas adaptability indicates the relative performance of a genotype under specific environmental conditions (Pour-Aboughadareh *et al.*, 2023) ^[25]. Therefore, selection of sugarcane genotypes based on yield stability and adaptability is essential prior to their recommendation for commercial cultivation in diverse agro-climatic zones.

Corresponding Author:
Vijeta Gupta
CCS HAU Regional Research
Station, Uchani, Karnal, Haryana,
India

Sugarcane (*Saccharum* spp.) is a highly heterozygous, polyploid and complex crop (Healey *et al.*, 2024) ^[7]. A key challenge in sugarcane improvement is the strong influence of genotype $\times$ environment interaction (GEI), which causes genotypes to perform inconsistently across environments, seasons and ratoon crops. Because breeding cycles span 10–12 years, the evaluation of clones across diverse locations is essential to identify stable and high-yielding varieties (Ram *et al.*, 2022) ^[27]. The phenotypic expression of yield and its component traits in sugarcane is governed by the effects of genotype (G), environment (E) and their interaction ($G \times E$). Among these, $G \times E$ interaction plays a crucial role in determining the differential response of genotypes across environments and often complicates the selection of superior varieties. Traditional analysis of variance (ANOVA) often fails to adequately capture GEI (Pour-Aboughadareh *et al.*, 2022) ^[26]. This has led to widespread adoption of advanced statistical tools including the joint regression approach of Eberhart and Russell (1966) ^[2], Additive Main Effects and Multiplicative Interaction (AMMI) model proposed by Gauch (1992) ^[6], GGE biplots proposed by Yan *et al.* (2000) ^[35], which visualize Genotype main Effect (G) plus Genotype by Environment (GE) interaction.

Eberhart and Russell suggested that a stable genotype should exhibit high mean performance, a regression coefficient (bi) close to unity and deviation from regression (S^2d) should be minimal (Makwana *et al.*, 2025) ^[17]. In recent years, the AMMI model has gained wide acceptance among sugarcane breeders as it effectively partitions the $G \times E$ interaction through principal component analysis and provides a comprehensive graphical interpretation of genotype performance across environments (Vinu *et al.*, 2025) ^[34]. The AMMI approach has been successfully employed to identify stable and widely adapted genotypes in multi-environment trials of sugarcane (Hossain *et al.*, 2023) ^[9]. The GGE biplot analysis has been used by several sugarcane breeders to classify the mega environment, assess genotype rankings and aid researchers in better understanding of complicated GE interactions in multi-environment breeding trials and agronomic investigations (Mehareb *et al.*, 2022) ^[19]. The GGE biplot determines the performance of crop cultivars in a variety of stress conditions, ideal cultivars, mega-environment and core testing sites (Lin *et al.*, 2025) ^[16].

This review provides a comprehensive synthesis of how Eberhart and Russell, AMMI and GGE biplots are used in sugarcane breeding globally.

Estimates of GE interaction and Stability analysis in sugarcane using AMMI biplot, Eberhart & Russell model and GGE biplot

Plant breeders face a continued challenge of identification of high yielding and stable genotypes across variable environments. The characterization of stable genotypes is often complicated by the frequent occurrence of genotype-by-environment interactions (GEI) (Mural, 2025) ^[20]. Environmental conditions strongly influence agricultural production, leading to considerable variations in yield. Such influence is discriminated when yield experiments are performed in various locations and in different years (Neisse *et al.*, 2018) ^[22]. Such influence is termed genotype-environment interaction (GEI). In multi-environment trial (MET) data, genotype $\times$ environment interaction (GEI) is commonly observed, and its presence affects crop performance, making cultivar selection a more complex process. The methods used to analyze GEI and evaluate genotypes are AMMI, GGE biplots and Eberhart & Russell joint regression method that are widely used to identify

high yielding and stable genotypes. Eberhart & Russell (1966) ^[2] suggested that regression coefficient ‘b’ and deviation from regression coefficient ‘ S^2d ’ might predict stable genotype. A cultivar with $b = 1$ and $S^2d = 0$ might be stable across divergent environmental conditions (Islam *et al.*, 2024) ^[11]. In addition, additive main effects and multiplicative interaction (AMMI) analysis is another approach, which combines both the ANOVA (with additive parameters) and Principal Component Analysis (with multiplicative parameters) into a single analysis (Gauch and Zobel, 1988) ^[5]. It is also an effective tool to diagnose genotype environment interaction patterns graphically (Kumar *et al.*, 2018) ^[15] and is a powerful tool for effective analysis and interpretation of multi-environment data structure in breeding programs. GGE focuses on $G + GE$, removing the environmental main effect since it is irrelevant for genotype ranking. It uses singular value decomposition (SVD) to plot genotype and environment scores and identifies mega-environments using “which -won-where” pattern. It is the best tool for defining mega-environments and helps in optimizing location selection in METs.

Vinu *et al.*, 2025 ^[34] evaluated seventeen elite sugarcane genotypes along with standard Co 86032 in three replications at two environments of Tamil Nadu (Nellikuppam: coastal region, and Alapuram: drought-prone area) during 2019–2021 seasons as two plant and one ratoon crops and identified Co 12009, Co 14002 and Co 14005 as stable, high-yielding and high-quality sugarcane varieties by focusing on the effects of genotype-by-environment ($G \times E$) interaction on yield and quality parameters and multivariate analyses using AMMI and GGE biplot. Similarly, Saravanan *et al.*, 2025 ^[28] assessed stability and yield potential of sugarcane clones under saline stress, comprising 20 environments during 2022 to 2024 using the AMMI (additive main effects and multiplicative interactions) and GGE (genotype $\times$ genotype interaction with environment) biplots. The yield potential and the stability of G 2008019 were confirmed through minimal ASV values and higher values for cane yield and juice-based quality traits. The biplots of AMMI I, AMMI II and GGE confirmed the constancy of G 2008019. Additionally, this clone also had good jaggery qualities, including 65.36% juice recovery, 91.84% juice purity, 11.32% jaggery recovery and 15.21 t/ha jaggery yield. The fibre content of the clone was 13.25%. These combined results indicate the suitability of clone G 2008019 for further utilization in the breeding cycle.

Mehareb *et al.*, 2022 ^[19] conducted seven field experiments at three experiment stations in Egypt using fourteen elite breeding lines along with one check variety (GT54-9) and stability was evaluated using GGE-biplots, AMMI model and the AMMI stability value (ASV) for cane and sugar yield during the 2018–2019, 2019–2020 and 2020–2021 seasons in a randomized complete block design with three replications. The clone G.2016–129 had a mean sugar yield and cultivar superiority index for sugar yield exceeding that of GT54-9, and hence was recommended for commercial planting. Therefore, the results of this study exposed that G.2016–95, F-150 and G.2016–129 with lowest ASV for cane yield by contrast, G.2009–11, G.2016–128, F-150 and G.2016–95 with lowest ASV for sugar yield, were stable clones for cane and sugar yields, respectively. Genotype $\times$ Environment interaction for cane yield, commercial cane sugar yield (CCS yield) and sucrose percentage in sugarcane (*Saccharum* spp.) using AMMI model was studied by Elayaraja *et al.*, 2022 ^[3] across three environments during 2017–18 and 2018–19 crop seasons to identify stable variety. Analysis of variance indicated that genotype, environment and genotype $\times$ environment interactions were highly significant across three

environments and showed high total variation for cane yield (38.56%), CCS yield (42.09%) and sucrose (35.87%). This revealed that environments were diverse and significantly influenced the stability of the genotypes. Based on mean performance across the environments and stability, the genotypes viz., Co 11015, Co 09004, Co 0240, Co 13014, and Co 14016 were found superior for both cane yield and CCS yield. For sucrose percentage, the genotypes, namely, Co 15021, Co 11015, Co 15007, Co 13001 and Co 16001 were found superior and stable across the environments.

Durai *et al.*, 2025 ^[1] conducted an experiment with 13 clones including seven test entries along with six released varieties as first plant, second plant and ratoon in RBD with three replications during the year 2022-23 and 2023-24 at ICAR-SBI, Coimbatore. The AMMI ANOVA for the sucrose, CCS percent, cane yield and CCS yield showed that significant individual effects of genotypes, environments and genotype $\times$ environment interaction. Multi-trait stability analysis for traits like sucrose, CCS percent, cane yield, CCS yield revealed that the genotypes Co 15003 and Co 86032 were highly stable. GGE analysis pinpointed that the genotype Co 17001 is highly stable than the standards Co 11015 and Co 86032 for sucrose content, cane and CCS yield. Thus, the genotypes Co 17001 and Co 15003 were stable and superior than the commercial varieties like Co 11015 and Co 86032 according to the AMMI, AMMI stability parameters and GGE for the cane yield and CCS yield and they may be promoted for commercial cultivation in target environment.

Additive main effects and multiplicative interaction (AMMI), as well as various AMMI-derived statistics, genotype, and genotype $\times$ environment interaction (GGE) models were employed by Kumar *et al.*, 2023 ^[14] on 24 sugarcane genotypes planted during two seasons (2017–18, 2018–19) under different induced salinity stress environments using saline water irrigation (i_w) to assess the genotype by the environment interaction for the cane yield, commercial cane sugar (CCS) yield, number of millable cane (NMC), single cane weight (SCW), and pol% in juice. As per AMMI Stability Value (ASV), G14 (Co 13033), G23 (Co 15026), G7 (Co 05009), G17 (Co 13036) and G2 (Co 15025) were the most stable genotypes for the cane yield. Whereas as per GSI (genotype selection index), genotypes G24 (Co 15027), G21 (Co 15023), G23 (Co 15026), and G17 (Co 13036) were found most stable. In the mean vs stability biplot analysis, G21 (Co 15023), G24 (Co 15027), G16 (Co 13036), G6 (Co 0238), and G20 (Co 14036) were found to be highly productive and stable genotypes for the cane yield. The superior and stable performance of early maturing notified varieties G21 (Co 15023) and G6 (Co 0238) for CY and CCS yield indicates that they will help the farmers to obtain sustainable income in saline soil conditions.

Fouladvand *et al.*, 2024 ^[4] conducted an experiment with 26 promising sugarcane genotypes along with four commercial varieties during 2017–2019 to determine a promising stable sugarcane genotype by analysing the effects of genotype $\times$ environment interactions for the sugarcane-growing areas of Khuzestan Province in Iran. According to an AMMI biplot, genotype g6 was considered to have special adaptation to the first location (Imam Khomeini), genotypes g8 and g15 were specifically adapted to the second location (Amir Kabir), and genotypes g10, g17, and g22 showed special adaptation to the third location (Mianab). Therefore, these genotypes are introduced for commercial cultivation in the mentioned locations.

The AMMI (Additive Main-effects and Multiplicative

Interactions) and GGE (Genotype $\times$ Genotype-Environment interaction) biplots were utilized by Sudhagar *et al.*, 2024 ^[31] to check stability of G2005047 under salinity through a multi-environment-based experiment (2015–2017). ANOVA revealed that the genotypic variation had the most significant effect followed by genotype $\times$ environment interaction and environment. G2005047 had the highest mean values for yield and quality traits with minimal ASV (AMMI stability value) indicating its good-yielding ability and stability which was further confirmed by AMMI I, AMMI II and GGE biplots. In the jaggery quality assessment trials (2018 and 2019), it yielded 37.1% increased jaggery over the check and also exhibited moderate resistance to red rot disease, less susceptibility to shoot borer (13.25%) and internode borer (25.35%) and resistance against sugarcane woolly aphid (SWA). Due to supremacy for yield, quality, better performance under salinized situations, and tolerance to disease and pests, the clone G2005047 was released as a variety CoG 7 in 2022.

An experiment was carried out by Verma *et al.*, 2024 ^[32] to ascertain the Gene $\times$ Environment interaction (GEI), yield stability and adaptability of 24 sugarcane varieties (*Saccharum officinarum* L.) across three locations in Chhattisgarh India using AMMI and GGE biplot analysis. In the analysis of variance, 75% of the cane yield variation was explained by the differences among varieties, 18.5% by the environment and 6.5% by GE interaction. According to AMMI and the GGE results, varieties G 19 (CoS 8436 local check), G12 (VSI 8005), the check variety G24 (CoC 0671), and G21 (Co 86032) were the most productive in tons of sugar per hectare and stable and recommended for the test environments. Genotypes, CoS 8436 and Co99006 were considered under specific adaptation to Ambikapur due to high cane yield and large IPCA score whereas, Co 99004 and VSI 8005 had high positive interaction with Kawardha while, CoJN 86-600 was found suitable for Jagdalpur.

Naidu *et al.*, 2018 ^[21] evaluated the relative performance of seventeen genotypes including three commercial varieties in five locations using a randomized block design with three replications by determining the magnitude of GE interactions during breeding program and identified promising ones that could be released for cultivation. The stability analysis was performed using the Eberhart & Russell's (1966) ^[2] model. The results showed that there were highly significant ($p < 0.001$) variations among the genotypes (G), environments (E) and GE interactions. Two genotypes LF82-2122 and LF60-3917 had higher yield and stability statistics for the two most important traits: cane and sugar yields. Thus, the genotypes can be recommended for adoption and cultivation on all soil types in Fiji.

Kaur *et al.*, 2025 ^[13] evaluated 33 diverse sugarcane (*Saccharum spp.* complex) genotypes for drought tolerance using Eberhart and Russell Regression and GGE biplot analyses. The Regression's model better identified the adaptability of genotype(s), while the GGE biplot effectively characterized the environments for their discriminating power. Traits like number of millable canes (NMC), sucrose (Pol%), total soluble solids (TSS%), relative water content (RWC), membrane stability index (MSI), proline and superoxide dismutase (SOD), emerged as the key yield contributor, highlighting their utility as selection indices. Significant higher expression of 10 drought-responsive genes (P5CS, SOD, DEH, BADH, IGS, cAPX, LEA, TPS, ProT, and DRP) in F 391/14 (CoPb 19182) and lower expression of four genes (SOD, DRP, ProT, and BADH) in CoJ 64 provided molecular insights into stress tolerance. These findings offer

valuable strategies for breeding resilient cultivars.

Studies on sugarcane stability were made by Singh *et al.*, 2024^[30] on 18 traits over three years (2016-19) with seven genotypes at Regional Research Station, PAU, Faridkot. Different multivariate statistical techniques were used for assessing the potential of CCS contributing traits and clonal stability. The observed significant differences due to varieties, years and their interactions were self explaining the role of genotypic differences and weather factors. CoPb 13181 was observed the most suitable clone for the region. Further, Eberhart & Russell's model was found more appropriate for judging the genotype to environment specificity while "GGE Biplot" was best to evaluate the environments for their discriminating power to genotypes.

Challenges in applying stability models

Despite the wide use of stability analysis methods such as AMMI, GGE biplot and Eberhart–Russell models, several practical and statistical limitations reduce their efficiency in crop improvement programs, especially in sugarcane multi-environment trials (METs).

Missing or Unbalanced Trial Data

Most stability models assume balanced datasets where all genotypes are evaluated across all environments with equal replications. However, in practical breeding programs, missing observations frequently occur due to poor germination, pest damage, lodging, ratoon failure, or experimental loss (Piepho, 1994)^[24]. Such imbalance can distort genotype $\times$ environment interaction (GEI) estimates and reduce the accuracy of stability parameters. Advanced mixed models can partially address this issue, but interpretation becomes more complex.

Large Number of Genotypes Reduces Interpretability

Modern breeding programs often evaluate hundreds of genotypes simultaneously across multiple locations and years. Although models like AMMI and GGE biplot are powerful, graphical interpretation becomes difficult when too many genotypes are included in the analysis. Overcrowded biplots may obscure mega-environment patterns and complicate the identification of stable and high-yielding cultivars (Pour-Aboughadareh *et al.*, 2022)^[26].

Lack of Environmental Covariates

Many conventional stability models rely only on genotype performance data and do not incorporate detailed environmental variables such as rainfall, temperature, soil properties, humidity, irrigation regime, or nutrient status. Without environmental covariates, it becomes difficult to explain the actual causes of GEI. Factorial regression and modern mixed models can integrate environmental information, but such datasets are often unavailable or incomplete in breeding programs (Malosetti *et al.*, 2013)^[18].

Variability Between Plant Crop and Ratoon Crop

In sugarcane, genotype performance frequently differs between plant cane and ratoon cane because ratoon crops experience altered root activity, nutrient availability, pest pressure and climatic stress. A genotype that performs stably in the plant crop may not maintain similar stability in ratoon conditions. This differential response complicates stability assessment and variety recommendation across crop cycles (Hu *et al.*, 2014)^[10].

Climate Variability Complicates GEI Patterns

Increasing climate variability due to irregular rainfall, heat stress, drought episodes and temperature fluctuations has intensified GEI complexity. Environmental unpredictability causes inconsistent genotype ranking across years and locations, making stability predictions less reliable. Traditional models may fail to capture dynamic climate-driven interactions unless long-term environmental datasets and advanced predictive approaches are incorporated (Hill, 1975)^[8].

Violation of Statistical Assumptions

Several stability models assume normal distribution of errors, homogeneity of variance and independence of observations. In real agricultural datasets, these assumptions are often violated due to heterogeneous environments and biological variability and can affect genotype ranking and reduce model reliability (Paul *et al.*, 2015)^[23].

Difficulty in Selecting the Most Appropriate Stability Model

Numerous parametric and non-parametric stability indices are available, and different models may produce conflicting genotype rankings. A genotype identified as stable by one method may not appear stable under another. Therefore, breeders often face difficulty in selecting the most biologically meaningful and statistically reliable approach for variety evaluation as stated by Pour-Aboughadareh *et al.*, 2022^[26].

Conclusion

AMMI, GGE biplot, and complementary stability models are indispensable tools for sugarcane improvement. They provide critical insights into GEI, identify stable and high-yielding varieties, define mega-environments, and optimize testing networks. Together, these tools enhance selection accuracy and support efficient variety release pipelines. Integrating GEI models with genomics, automation and environmental data will further strengthen next-generation sugarcane breeding.

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