Agr. Nat. Resour. 57 (2023) 895–906

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Evaluating elite genotypes in diverse environments for cane and sugar yield stability and adaptability in Thailand

Juthamas Khruengpatee[a], Prasit Jaisil[a,b], Nakorn Jongrungklang[a,b], Patcharin Songsri[a,b,c,*]

[a] *Department of Agronomy, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand*
[b] *Northeast Thailand Cane and Sugar Research Center (NECS), Khon Kaen University, Khon Kaen 40002, Thailand*
[c] *Center of Knowledge and Technology for Cane and Sugar, Bangkok 10900, Thailand*

Article Info

Article history:
Received 18 August 2023
Revised 25 October 2023
Accepted 27 October 2023
Available online 31 October 2023

Keywords:
Additive main effect and multiplicative interaction (AMMI) biplot,
Genotype × environment interaction,
Multi-environment trials (METs),
Ratooning ability,
Sugarcane breeding

Abstract

Importance of the work: The genotype-environment interaction (GEI) influences the stability and ranking of genotypes investigated in various environments.
Objectives: To identify significant variance in the GEI in multi-environment trials and to assess the performance and stability of elite sugarcane clones under various agro-ecological environments.
Materials & Methods: Eight top sugarcane clones were examined in 22 multi-location yield trials carried out from 2014 to 2017. The additive main effect and multiplicative interaction (AMMI) biplot was used to conduct stability assessments for cane yield, sugar yield and commercial cane sugar cultivars.
Results: Reducing the number of crop years was the most effective option because the variance component of genotype × location was larger than for genotype × crop year and the fact that all traits showed a significant association between the second and third crop classes. There was a significant relationship between cane yield and sugar yield for two- and three-crop classes. The correlation ranking revealed a substantial association between both parameters, with correlation coefficients values for cane yield and sugar yield of 0.9286 and 0.9524, respectively These values were statistically significant.
Main finding: By indirectly choosing across environments, the AMMI and genotype and environment interaction biplots facilitated the selection of stable and high-yield sugarcane genotypes and reduced the necessity for regional trials, which saved resources. The general and specific adaption cultivars that produced high cane and sugar yields were Kps01-12, KK3, LK92-11 and TBy28-0348.

* Corresponding author.
E-mail address: patcharinso@kku.ac.th (P. Songsri)

https://doi.org/10.34044/j.anres.2023.57.5.16

Introduction

The rankings of crop genotypes evaluated under various conditions alter due to genotype-environment interaction (GEI); however, the performance of genotypes is not proportionate to environmental changes, such as drought and soil fertility, making it challenging to select superior genotypes at the regional level (Tiawari et al., 2011). Nonetheless, knowledge of the GEI helps in the design of breeding programs (Tarakanovas and Ruzgas, 2006), with such knowledge mostly derived via multi-environment trials (METs) to identify the most stable and high-yielding genotypes.

The GEI effects can be minimized by selecting and determining genotypes that are more stable in a variety of situations (Eberhart and Russell, 1966). Two multivariate analytical methods (biplot analysis) have recently been developed and are now widely used to evaluate genotypes by environment in two-way data (Dehghani et al., 2006; Pobkhunthod et al., 2022). These methods include the additive main effect and multiplicative interaction (AMMI) biplot (Gauch, 1988; Zobel et al., 1988; Chatwachirawong et al., 1999) and the genotype and environment interaction (GGE) biplot (Yan et al., 2010; Pobkhunthod et al., 2022). Testing of genotype × location (GL) and genotype × crop year (GC) interactions is possible using METs carried out over several crop years. The yield potential and yield stability of sugarcane cultivars can be determined by these two components of the genotype-environment (GE) interaction and has been used for quantifying the performance of sugarcane genotypes for cane yield and sucrose content or for derived sucrose yield in breeding programs in several countries, including Australia (Mirzawan et al., 1994), USA (Glaz and Kang, 2008), Venezuela (Rea et al., 2011 and Rea et al., 2016), Thailand (Klomsa-ard et al., 2013; Khruengpatee et al., 2023), Brazil (Mattos et al., 2013) and South Africa (Dlamini and Ramburan, 2016). The methods allow breeders to select the genotypes with general adaptation to use under a wide range of conditions and to choose the genotypes with specific adaptation to use in specific environments (Parfitt and Thomas, 2001). The utilization of the GGE biplot and AMMI models has been proposed by Kaya (2006) to reinforce stability and superiority indices in the identification of genotypes exhibiting both specific and wide adaptability. Multi-environment trials play a crucial role in accurately assessing and rating candidate cultivars, as well as identifying suitable selection or production conditions (Yan et al., 2007). According to Yan and Holland (2010), the use of this approach has the potential to enhance breeding efficiency. Additionally, Gauch and Zobel (1997) suggested that it might contribute to the enhancement of yield production competitiveness. Breeders could decide between genotypes with general adaptation to use in a wide range of environments and genotypes with specific adaptation to use in particular environments due to these approaches (Parfitt and Thomas, 2001).

The research by Klomsa-ard et al. (2013) investigated nine locations across three regions in Thailand in 2005. These zones are now more widely distributed and have even reached the eastern and western regions. In their trial, only clay soil received irrigation. Therefore, extra knowledge is now required to enable the production area to be expanded to include more varied settings while maintaining the same growing season. They obtained the KK3 variety from earlier study and identified the most effective test zones, which were in northern, central and northeastern Thailand. According to Rashidi et al. (2013), the characteristics of a selection and testing program were determined by the size and nature of GEI in various situations. Thailand's sugarcane crop was subject to several limitations that decrease yields. Selecting the environment that spans all sugarcane-producing systems was important. The management of rainfed crops in considering changed climatic conditions would be closely related to the development of the sugar industry. Unexpected rainfall has added uncertainty, which exacerbates the yield crisis during a drought. The genotypes with specialized adaptations to ecosystems and soil types (Costa et al., 2013) should be utilized under irrigated conditions (Kusangaya et al., 2014), whilst the widely adapted variety should be used under rainfed conditions.

An important question is how to minimize the number of METs in breeding programs for sugarcane. Therefore, the aims of this study were to identify the genotype response patterns and yield stability across environments, as well as to assess the productivity and stability of potential sugarcane genotypes in terms of cane yield, sugar yield and commercial cane sugar (CCS) variety under various agro-ecological environments.

Materials and Methods

The genotypes of sugarcane that were studied were derived from breeding projects undertaken by different organizations in Thailand. Eight elite sugarcane lines—KK06-501 (G1), CSB06-2-15 (G2), CSB06-2-21 (G3), TBy27-1385 (G4) and TBy28-0348 (G5), as well as three control cultivars, KK3 (G6), LK92-11 (G7) and Kps01-12 (G8)—were planted in each experimental field. The multi-location yield experiments from 2014 to 2017 were examined in the following part of the research investigation. There were 16 test sites with three crops (plant cane, first ratoon and second ratoon) and there were 22 test sites with two crops (plant cane and first ratoon).

For each experimental site, a randomized complete block design with four replications was used. The plot size (48 m^2) was 8 m in length and had four planting rows with 1.5 m between rows and 0.5 m between plants. Three buds per set of double cane were hand-planted. In each case, planting was scheduled either in the early rainy season (April–June) or the late rainy season (October–January). Where available, supplemental irrigation was provided once or twice throughout the tillering and elongation stages, whereas the noon irrigated sites were solely rainfed. Based on soil analyses performed at each location before planting and 4–5 mth after planting, the fertilizer was applied to the plant, first and second ratoon canes at rates of 312.50 and 468.75 kg/ha/time, respectively. To maintain optimal conditions, disease infestation control and insect damage and weed management were carried out as required. The planted cane crops lasted 10–14 mth, whereas the ratoon cane crops lasted 12 mth.

Nearby meteorological stations provided weather and precipitation information. Additionally, geographic information was gathered for the 22 test sites (2 crop years: plant cane and 1^{st} ratoon) and 16 test sites (3 crop years: plant cane, 1^{st} ratoon and 2^{nd} ratoon). Soil samples from every experimental field that were taken from a depth of 0–30 cm before planting were analyzed to determine the physical and chemical characteristics of the soil. The soil was analyzed for pH, soil organic matter (OM) and soil texture (%sand, %silt and %clay), with the results shown in Table 1.

At the final harvest, Qualitative data was collected and recorded at final harvest, with the parameters determined from the two middle rows and used to determine the cane yield (based on kilograms per plot) and the number of millable canes (based on stalks/plot; STKNO), which were then counted and cut at ground level. Eight canes were randomly selected from the two middle rows to gather the quantitative data. Next, the crop from each subplot was weighed, bundled and clearly identified based on the plot number and variety. Then, each 8-stalk subsample was taken to the laboratory where the cane juice was extracted to analyze the °Brix, polarity and fiber content. The CCS yield was calculated using Equation 1:

$$\text{CCS} = \left[\frac{3}{2}\text{P}\left(1- \frac{(\text{F}+5)}{100}\right)\right] - \left[\frac{1}{2}\text{B}\left(1- \frac{(\text{F}+3)}{100}\right)\right] \tag{1}$$

where P is the polarity Pol at 20°C, B is the °Brix at 20°C and F is the percentage fiber content.

Table 1 Geographical and weather data and physico-chemical soil properties across 22 test locations

Location	Code	Conditions	Planting date	Annual rainfall (mm)	% Sand	% Silt	% Clay	% Organic matter	pH
Nakhon Sawan	NSN1	rainfed	12 Dec 14	1,353	25.76	35.16	39.08	1.90	5.89
Khamphaeng Phet	KPT1	rainfed	26 Nov 14	1,360	41.06	37.92	21.02	0.35	6.02
Sa Kaeo	SKW1	rainfed	7 Jan 15	1,049	27.86	35.30	36.84	1.99	6.59
Nakhon Ratchasima	NMA1	rainfed	20 Dec 14	1,029	76.03	18.47	5.50	0.92	5.43
Nakhon Ratchasima	NMA2	rainfed	20 Dec 14	1,307	81.22	13.07	5.71	2.10	7.07
Rayong	RYG1	rainfed	18 Nov 14	1,314	89.68	9.31	1.01	0.62	5.58
Udon Thani	UDN1	rainfed	19 Nov 14	1,317	70.01	19.71	10.28	1.11	5.91
Rayong	RYG2	rainfed	18 Dec 14	1,307	77.84	10.99	11.17	0.20	5.97
Nakhon Sawan	NSN2	irrigated	8 Dec 14	1,444	29.79	48.95	21.26	1.71	6.15
Kanchanaburi	KRI1	irrigated	23 Dec 14	1,135	60.06	23.69	16.25	0.96	7.31
Suphan Buri	SPB1	irrigated	13 Dec 14	971	28.98	30.65	40.37	1.07	7.06
Sa Kaeo	SKW2	irrigated	27 Dec 14	1,095	21.73	27.64	50.63	1.79	5.90
Khon Kaen	KKN1	irrigated	21 Nov 14	1,267	79.35	16.13	4.52	0.47	6.08
Nakhon Ratchasima	NMA3	irrigated	24 Dec 14	1,059	54.89	29.40	15.71	1.25	7.03
Kanchanaburi	KRI2	rainfed	13 May 15	971	79.91	17.06	3.03	1.06	5.65
Suphan Buri	SPB2	rainfed	4 Apr 15	1,033	66.14	26.72	7.14	0.69	7.30
Prachuap Khiri Khan	PKN1	rainfed	20 May 15	685	59.57	31.1	9.33	0.40	5.43
Nakhon Sawan	NSN3	rainfed	21 May 15	1,132	11.42	31.02	57.66	1.26	7.03
Nakhon Sawan	NSN4	irrigated	10 Jun 15	1,444	11.90	55.96	32.14	2.14	6.23
Nakhon Sawan	NSN5	irrigated	17 Jun 15	1,341	67.67	22.73	9.60	1.20	6.94
Suphan Buri	SPB3	irrigated	29 May 15	971	36.89	41.59	21.52	1.29	6.27
Phichit	PCK1	irrigated	26 Jun 15	1,178	10.01	38.00	60.99	3.80	6.06

The sugar yield (SYLD) was calculated using Equation 2:

$$SYLD = \left(\frac{CCS \text{ x Cane yield}}{100}\right) \quad (2)$$

Analysis of variance and combined analysis of variance were used to examine the data. All attributes were assessed for correlation between two crop years (plant cane and the first ratoon) and three crop years (plant cane, the first ratoon and the second ratoon), where applicable. All tests were considered significant at $p < 0.05$. The R software program (R Core Team, 2010) was utilized to implement the AMMI and GGE biplots for the analysis of cane yield, sugar yield and CCS stability.

Results

For cane yield, sugar yield and CCS, the analysis of variance components revealed highly significant impacts for location (L), genotype (G) and crop year (C), with significant interactions between these sources of variance. The mean sum of squares from the combined analyses of variance for the eight sugarcane genotypes with cane yield, sugar yield and CCS evaluated over three crop years in 16 locations in plant cane (PC), first ratoon cane (1RC), second ratoon cane (2RC) and average of three crop classes indicated that genotype × environment interactions also played a significant role in the total variations in LC, LG, CG and LCG, respectively. The primary factor contributing to the differences in cane yield and CCS was C, which accounted for 60.73% and 70.22%, respectively, of the total variations while L contributed 23.16% and 12.58%, respectively, to the variations and G accounted for 9.16% and 12.09%, respectively, of the variations. In terms of sugar yield, the primary sources of variation were L, followed by G and C, which accounted for 41.76%, 23.78% and 23.56%, respectively, of the total variances (Table 2). The mean sum of squares obtained from the combined analyses of the variance of the eight sugarcane genotypes, evaluated for cane yield over three crop years in 22 locations were used to assess the impact of genotype × environment interactions on the total variations in LC, LG, LCG and CG. These interactions were statistically significant, as shown in Table 3.

Table 2 Mean squares from combined analyses of variance of eight sugarcane genotypes for cane yield, commercial cane sugar (CCS) yield and CCS evaluated during three crop years in 16 locations

Source of variation	df	Mean square		
		Cane yield (t/ha)	Sugar yield (t CCS/ha)	CCS
Location (L)	15	1011.23** (23.16%)	22.62** (41.76%)	119.83** (12.58%)
Rep within L	48	13.16 (0.30%)	0.26 (0.48%)	5.614 (0.59%)
Crop year (C)	2	2651.51** (60.73%)	12.76** (23.56%)	669.04** (70.22%)
Genotype (G)	7	400.09** (9.16%)	12.88** (23.78%)	115.17 ** (12.09%)
L × C	30	216.27** (4.95%)	3.823** (7.06%)	25.85** (2.71%)
L × G	105	33.35** (0.76%)	0.698** (1.29%)	6.11** (0.64%)
C × G	14	26** (0.60%)	0.76** (1.40%)	5.23** (0.55%)
L × Y × G	210	11** (0.25%)	0.28** (0.52%)	4.32** (0.45%)
Pooled error	1104	3.43 (0.08%)	0.09 (0.17%)	1.67 (0.18%
CV (%)		15.21	18.93	9.81

df = degrees of freedom; Rep = replication; CV = coefficient of variation;
** = highly significant ($p < 0.01$); The number in the parenthesis is the percentage of the mean square.

Table 3 Mean squares from combined analyses of variance of eight sugarcane genotypes with cane yield, commercial cane sugar (CCS) yield and CCS evaluated during two crop years in 22 locations

Source of variation	df	Mean square		
		Cane yield (t/ha)	Sugar yield (t CCS/ha)	CCS
Location (L)	21	846.15** (31.81%)	15.77** (49.48%)	88.07** (7.48%)
Rep within L	66	12.06 (0.45%)	0.24 (0.77%)	4.58 (0.39%)
Crop year (C)	1	1227.90** (46.19%)	0.15^{ns} (0.47%)	949.99** (80.71%)
Genotype (G)	7	356.06** (13.39%)	11.64** (36.52%)	100.47** (8.54%)
L × C	21	171.78** (6.46%)	2.57** (8.05%)	16.14** (1.37%)
L × G	147	24.65** (0.93%)	0.53** (1.67%)	6.27** (0.53%)
C × G	7	6.00** (0.23%)	0.63** (1.98%)	5.93** (0.50%)
L × Y × G	147	10.00** (0.38%)	0.25** (0.78%)	3.93** (0.33%)
Pooled error	990	3.57 (0.13%)	0.09 (0.28%)	1.67 (0.14%)
CV (%)		14.62	18.42	10.44

df = degrees of freedom; Rep = replication; CV = coefficient of variation;
ns = not significant ($p \geq 0.05$); ** = highly significant ($p < 0.01$); The number in the parenthesis is the percentage of the mean square.

Based on empirical observation and the subsequent analysis, the predominant source of variance in cane yield could be attributed to the factors of C > L > G. Conversely, for CCS, the primary contributors to variance were C > G > L. Furthermore, the variation for the yield of sugar was highest for L, followed by G and C. The present study involved the comparison of complex features across many crop years and locations in order to identify discernible patterns.

There were high cane and sugar yields in the genotypes Kps01-12 (G8), KK3 (G6) and LK92-11 (G7). The eight genotypes (Fig. 1) covered three crop classes on average and four different conditions on 16 sites for plant cane (PC), first ratoon cane (1RC) and second ratoon cane (2RC). High sugar cane and plant cane yields were observed for the eight genotypes that were planted early, covering four conditions in 22 locations for the average of two crop classes in the Kps01-12 (G8), KK3 (G6) and LK92-11 (G7) genotypes (Fig. 1). The overall average of the cane and sugar yields from the three crop classes in the 16 locations was 76.08 t/ha and 10.03 t CCS/ha, respectively. Kps01-12 (G8), KK3 (G6) and LK92-11 (G7) were the genotypes that had the highest cane and sugar yields, respectively. Under drought conditions, the Kps01-12 genotype still produced high cane and sugar yields.

KRI1, SPB1, NSN3 and NSN4 were the main contributing factors with cane and sugar yields of 85.45 t/ha and 11.63 t CCS/ha, 131.35 t/ha and 18.41 t CCS/ha, 81.19 t/ha and 10.46 t CCS/ha, and 100.54 t/ha and 15.71 t CCS/ha, respectively. With irrigated conditions with certain developmental phases or prolonged rainfall, the KK3 genotype had high cane and sugar yields. Specifically, NSN1, NSN2, SKW2, KKN1, NMA3 and NSN5 were identified as contributing factors, with corresponding yields of 115.25 t/ha and 14.24 t CCS/ha, 130.98 t/ha and 17.60 t CCS/ha, 68.14 t/ha and 9.62 t CCS/ha, 86.53 t/ha and 11.47 t CCS/ha, 89.62 t/ha and 11.76 t CCS/ha, and 83.45 t/ha and 10.92 t CCS/ha, respectively. The LK92-11 and TBy28-0348 genotypes produced high cane and sugar yields when the soil was rich and well-watered; specifically for NMA1, PCK1, NMA1 and SPB3 as the main components resulting in yields of 102.41 t/ha and 12.14 t CCS/ha, 45.04 t/ha and 5.90 t CCS/ha, 80.49 t/ha and 12.54 t CCS/ha, and 136.31 t/ha and 21.23 t CCS/ha, respectively. (Table 4).

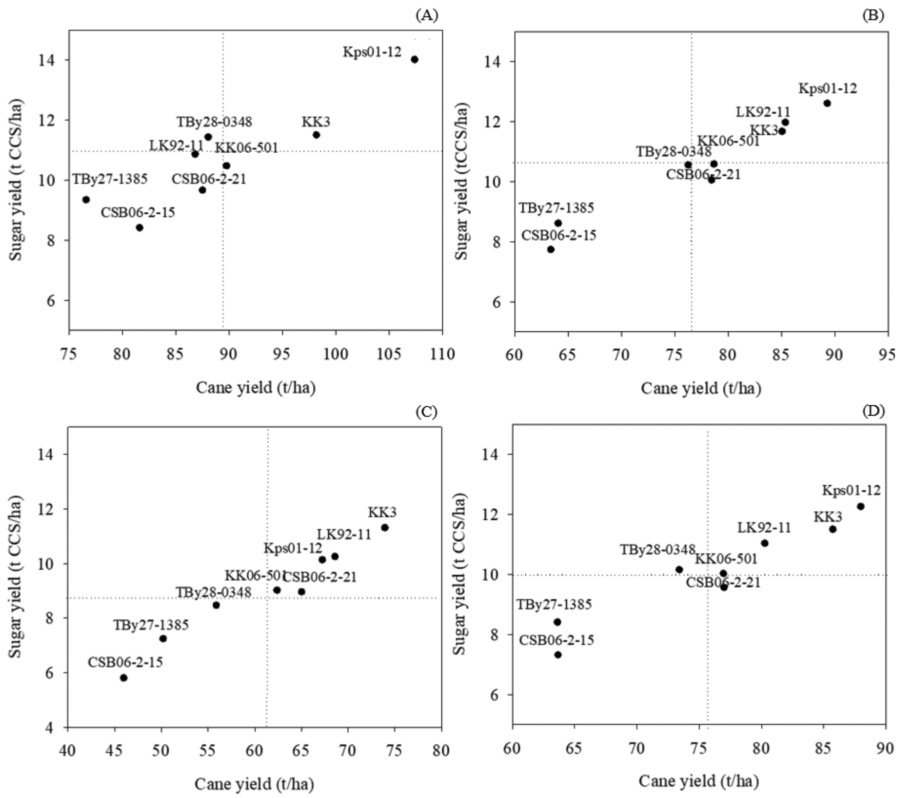

Fig. 1 Mean yields of eight genotypes planted as early cover under four conditions across 16 locations for: (A) plant cane; (B) first ratoon cane; (C) second ratoon cane; (D) average of three crops, where CCS = commercial cane sugar

Table 4 Site mean cane and mean commercial cane sugar (CCS) yields of eight elite sugar cane lines (G1–G8) for three crops at 16 locations in Thailand

Location/Genotype	G1	G2	G3	G4	G5	G6	G7	G8	Mean
NSN1[1]	81.99	59.58	87.95	71.15	88.82	115.25	92.42	105.22	87.80
NSN1[2]	10.34	6.62	10.57	8.24	10.30	14.24	11.29	12.29	10.49
SKW1[1]	60.31	64.26	66.24	76.89	64.72	74.15	65.52	72.08	68.02
SKW1[2]	8.52	7.64	8.22	11.08	9.32	10.33	9.30	10.32	9.34
NMA1[1]	75.43	38.49	76.70	61.35	80.49	86.90	75.15	76.40	71.36
NMA1[2]	9.31	4.03	9.30	7.85	12.54	11.10	10.35	11.59	9.51
NMA2[1]	72.72	80.06	84.34	57.96	73.62	67.49	102.41	84.39	77.87
NMA2[2]	7.05	7.63	9.16	6.17	8.51	7.22	12.14	10.47	8.54
NSN2[1]	97.31	76.15	99.89	68.71	89.31	130.98	97.51	123.86	97.97
NSN2[2]	12.29	8.85	11.88	8.65	11.30	17.60	12.77	16.75	12.51
KRI1[1]	71.07	81.52	60.15	51.61	65.51	68.84	69.06	85.45	69.15
KRI1[2]	9.86	9.28	8.34	8.05	10.19	9.50	10.62	11.63	9.68
SPB1[1]	110.35	106.34	107.56	105.77	98.33	112.25	115.32	131.35	110.91
SPB1[2]	14.85	10.83	11.62	13.02	13.16	16.23	16.03	18.41	14.27
SKW2[1]	50.60	48.70	58.53	34.99	57.26	68.14	68.34	64.72	56.41
SKW2[2]	6.65	6.69	7.67	5.37	8.85	9.62	9.57	9.21	7.95
KKN1[1]	96.02	47.55	66.63	47.56	60.47	86.53	79.49	84.19	71.06
KKN1[2]	11.02	5.12	7.33	5.09	7.33	11.47	10.20	11.15	8.59
NMA3[1]	65.59	44.00	75.24	47.93	72.00	89.62	58.84	71.68	65.61
NMA3[2]	8.18	4.40	9.17	6.27	10.02	11.76	7.95	10.14	8.49
KRI2[1]	63.63	40.19	51.19	54.02	72.08	59.87	77.44	71.77	61.27
KRI2[2]	8.76	4.98	6.51	7.68	10.67	8.26	11.50	11.53	8.74
NSN3[1]	63.09	56.38	73.13	47.96	46.43	65.02	58.36	81.19	61.45
NSN3[2]	8.19	6.38	8.89	6.40	5.69	8.12	7.48	10.46	7.70
NSN4[1]	99.78	61.66	89.79	65.29	73.05	102.16	93.75	100.54	85.75
NSN4[2]	14.84	7.83	12.06	9.72	11.53	14.58	14.52	15.71	12.60
NSN5[1]	56.90	73.50	63.50	70.62	58.51	83.45	66.94	70.25	67.96
NSN5[2]	7.25	9.08	8.41	8.52	7.39	10.92	8.45	9.49	8.69
SPB3[1]	121.33	99.11	123.08	115.46	136.31	114.27	118.67	140.82	121.13
SPB3[2]	17.78	12.83	18.10	17.10	21.23	17.95	18.39	20.95	18.04
PCK1[1]	45.06	41.29	47.99	40.82	37.54	46.80	45.04	43.64	43.52
PCK1[2]	5.50	4.88	5.74	5.21	4.39	5.03	5.90	5.89	5.32
Mean[1]	76.95	63.67	77.00	63.63	73.40	85.73	80.27	87.97	76.08
Mean[2]	10.02	7.32	9.56	8.40	10.15	11.50	11.03	12.25	10.03
Ranking[1]	5	7	4	8	6	2	3	1	
Ranking[2]	5	8	6	7	4	2	3	1	

[1] = cane yield (t/ha); [2] = sugar yield (t CCS/ha)

The correlation of cane yield, sugar yield and CCS for the averages of two and three crop classes revealed that all of the traits were strongly correlated for between two and three crop years, with r values of 0.8265, 0.8384 and 0.7368, respectively, which were all highly significant (Figs. 2A, 2C, 2E). Two crop years and three crop years were highly correlated, according to the ranking for cane yield and sugar yield averages for the two and three crop classes, with r values of 0.9286 and 0.9524, respectively, which were highly significant in the descending order Kps01-12, KK3 and LK92-11. While the ranking based on correlation between CCS and crop years was similarly strongly associated for the most recent two and three crop years, with an r value of 0.9762, which was highly significant, the rankings changed to Kps01-12, TBy28-0348, KK3 and LK92-11, respectively (Figs. 2B, 2D, 2F).

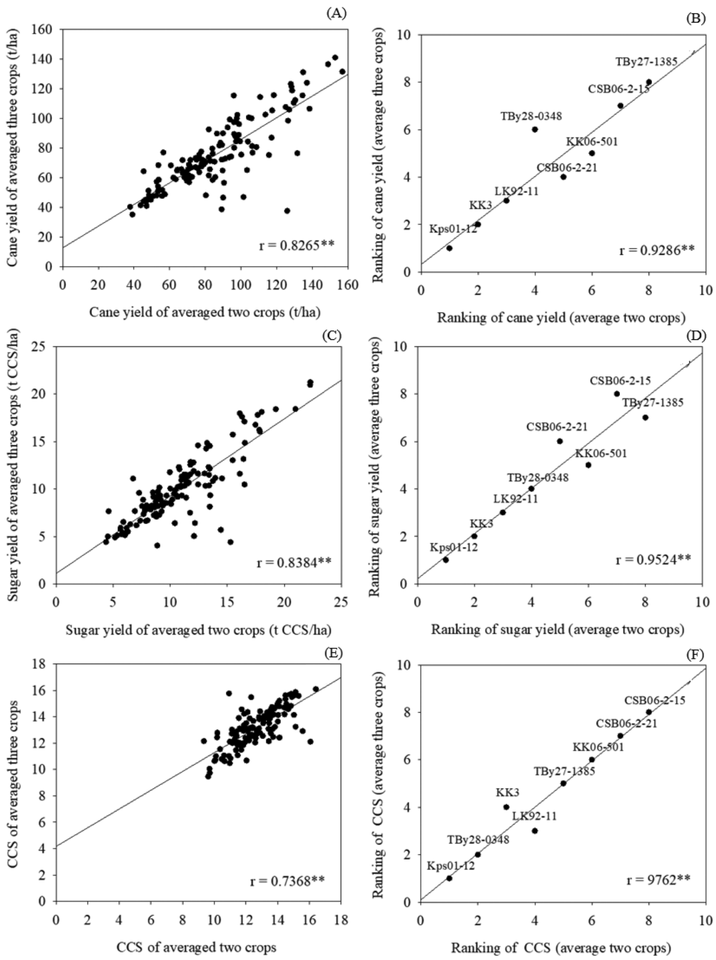

Fig. 2 Mean yields of eight genotypes planted across 22 locations for averages of three crops and two crops: (A) cane yield; (C) sugar yield; (E) commercial cane sugar (CCS). Correlation rankings of eight genotypes for three crops versus two crops: (B) cane yield; (D) sugar yield; (F) CCS, where r = correlation coefficient and ** = highly significant ($p < 0.01$)

The analysis of variance performed across various environments revealed significant variations in cane yield, sugar yield and CCS (sucrose content) over the 22 environments. Additionally, the research also identified significant interactions between genotype and environment (GE interactions). The observed GE interaction effects indicated that genotypes had differential responses to changes in environmental variables. The observed variances may be ascribed to distinct meteorological and edaphic conditions present in the respective locations. The analysis of variance revealed that a significant portion of the total sum of squares for cane yield was attributed to several factors. Specifically, 77.35% of the variation was explained by environmental effects, 6.68% by genotype effects and 13.53% by the interaction between genotype and environment. Similarly, the analysis of variance results for sugar yield indicated that 62.81% of the variation was due to environmental effects, 33.97% to genotype effects and 2.27% to the interaction between genotype and environment. Lastly, for CCS, the analysis of variance showed that 44.57% of the variation was attributable to environmental effects, 48.32% to genotype effects and 4.30% to the interaction between genotype and environment (Table 5). The first visual interpretation of the biplot was based on the variance caused by the multiplicative effect caused by the GE interaction and the additive main effects of genotypes and environments (AMMI2). The abscissa coordinates on the first of principal components (PC1) show the main effects (the overall cane yield, sugar yield and CCS mean of the tested genotypes). The genotypes Kps01-12 (G8), KK3 (G6) and LK92-11 (G7) contributed the most to the GE interaction for the average of two crop classes for cane production. Since the coordinates on the axis had the lowest interaction principal components axis (IPCA1) values (Fig. 3A), LK92-11 (G7), CSB06-2-21 (G3) and TBy28-0348 (G5) provided the least contribution (moderate and most stable). The largest yields, which were above average, were produced by the clones G8, G6 and G7. According to Figs. 3B and 3C, the promising clones Kps01-12 (G8), KK3 (G6), LK92-11 (G7) and TBy28-0348 (G5) had the greatest sugar yield and CCS values, as well as high or moderate stability.

The observed environments were categorized into three mega-environments for cane yield and sugar yields and five mega-environments for CCS, as seen in Figs. 4A, 4B and 4C. The first mega environment for cane yields encompassed all sites except SPB3, KRI2 and NSN5 (Fig. 4A). Similarly, the first mega environment for sugar yields included all locations except for SPB3, KRI2, NSN5, KPT1 and PKN1 (Fig. 4B). Fig. 4 provides a visual aid to illustrate the spatial separation between each environment and the ideal environment, referred to as the "model studied environment," situated in the center of the concentric circles. Hence, it can be concluded that SPB3, KRI2, NSN5, KPT1 and PKN1 had the highest level of representativeness and discriminatory power in terms of cane yield and sugar yield. However, it is advisable to exclude these regions from testing.

Based on the ability for rapid adaptation to the environmental conditions, responsive behavior, positive exploitation of the interactive effect of the environment or adaptive synergism in the environmental conditions, the observed positive interactions between genotypes and environments classified the genotype groups as adapted and most stable.

Table 5 Analysis of variance for additive main effect and multiplicative interaction model applied to cane yield, sugar yield and commercial cane sugar (CCS) of eight genotypes for average of two crops at 22 locations in Thailand

Source	df	Cane yield		Sugar yield		CCS	
		MS	%Total SS	MS	%Total SS	MS	%Total SS
Environment (E)	21	744.90**	77.35	11.91**	62.81	60.15**	44.57
Genotype (G)	7	192.89**	6.68	6.44**	33.97	65.21**	48.32
G × EInteraction	147	18.61**	13.53	0.43**	2.27	5.81**	4.30
PC1	27	34.40**	33.95	0.96**	41.15	14.25**	45.08
PC2	25	28.22**	25.79	0.61**	24.10	8.21**	24.04
PC3	23	21.61**	18.16	0.41**	14.73	4.71**	12.68
PC4	21	13.70**	10.51	0.26**	8.47	3.26**	8.03
PC5	19	7.95**	5.52	0.21**	6.36	2.60*	5.79
PC6	17	5.50^{ns}	3.40	0.12^{ns}	3.35	1.46^{ns}	2.90
PC7	15	4.87^{ns}	2.67	0.08^{ns}	1.84	0.84^{ns}	1.47
PC8	13	0.00^{ns}	0.00	0.00^{ns}	0.00	0.00^{ns}	0.00
Residuals	462	4.25		0.092		1.47	

df = degrees of freedom; MS, mean squares; SS = sum squares; PC = the principal components;
ns = non-significant; * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$)

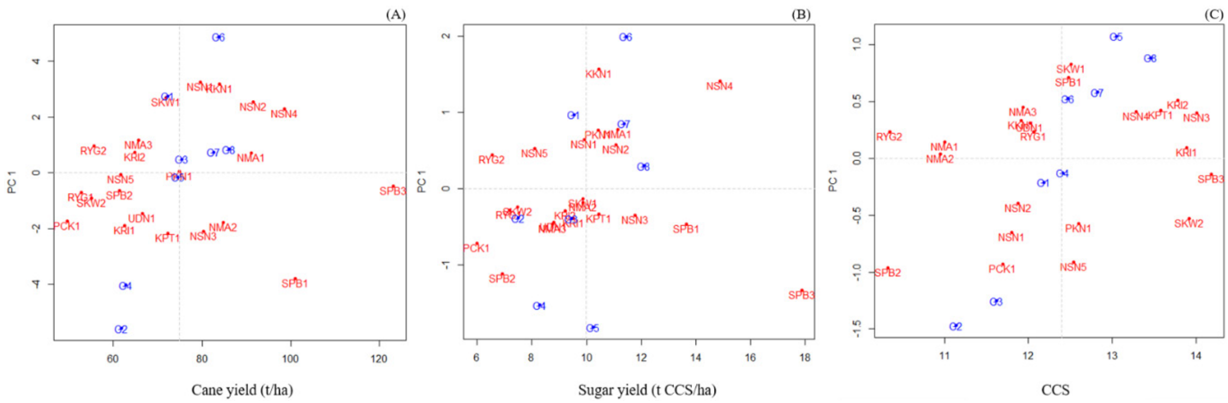

Fig. 3 Additive main effect and multiplicative interaction biplot with the first of principal components (PC1) × eight sugarcane genotypes (in blue) at 22 locations (in red) in Thailand for cover plant cane and first ratoon cane: (A) cane yield average of two crop classes; (B) average sugar yield of two crop classes; (C) commercial cane sugar yield average of two crop classes

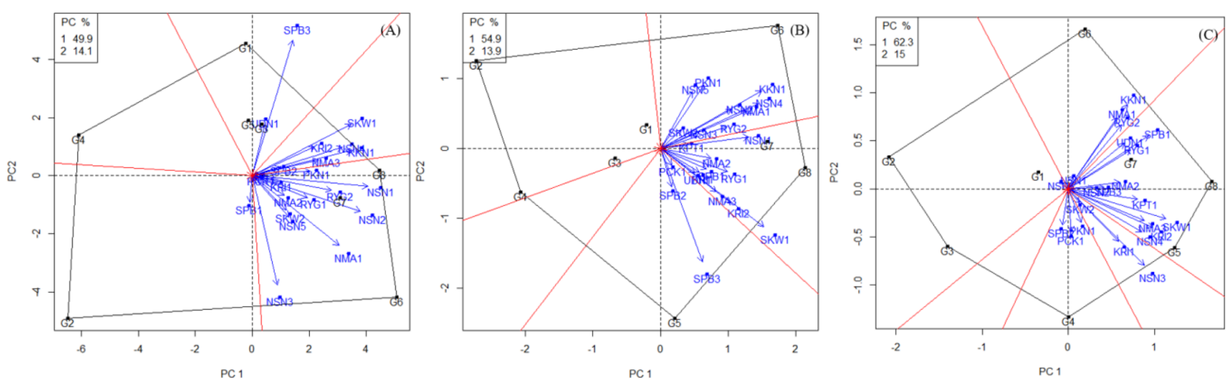

Fig. 4 "Which-won-where" polygon view of genotype and environment interaction biplot of eight sugarcane genotypes at 22 locations in Thailand for cover plant cane and first ratoon cane: (A) the first and two of principal components (PC1 and PC2) for cane yield; (B) the first and two of principal components (PC1 and PC2) for sugar yield; (C) the first and two of principal components (PC1 and PC2) of commercial cane sugar, where the "model studied environment," identify genotypes suitable for the test environments and dotted red line = divide similarly responding environments or maga-environment

In situations where conducting an experiment in a controlled and stable environment is not achievable or when crop loss occurs due to adverse conditions, it is advisable to incorporate data from alternative environments within the first mega-environment of cane and sugar yields that exhibit high stability. Notably, environments such as NMA1, NSN1 and KKN1, should be considered for future evaluation and recommendations. These test locations may be appropriately evaluated for consideration in the development of the early phases of sugarcane selection because of their small GE interactions. Genotypes with general adaptability tend to function well and can be chosen with greater safety in environments with high levels of stability. On the other hand, because there was a tendency to choose genotypes with a specific adaptation to these sites, settings with a high GE interaction (high instability), such as NSN5, SPB3 and KRI2, should be avoided in the early phases.

Discussion

Breeding systems use clonal multiplication to select individuals via a series of sequential phases. In the most advanced stages of selection, replicated experiments are used for evaluating the topmost elite clones in METs at representative locations. A MET permits the evaluation of GL and GC interactions over a number of crop years. The yield potential and yield stability of sugarcane varieties are determined by these two aspects of the GE interaction, which have been quantified for cane yield and sucrose content or for derived sucrose yield in breeding programs at various locations, including Australia (Natarajan et al., 2020), Brazil (Mattos et al., 2013), the USA (Kimbeng et al., 2009), Florida (Glaz and Kang, 2008), Pakistan (Khan et al., 2013), South Africa (Ramburan and Nxumalo, 2017), Ethiopia (Tena et al., 2019), Venezuela (Rea et al., 2011), Reunion Island (Guilly et al., 2017) and Thailand (Serivichayaswadi et al., 1997; Klomsa-ard et al., 2013). All of these MET study examples include regions widely dispersed throughout sizable, cultivated areas, which are essentially formed by ecosystems that are more or less diverse in many aspects, such as soil type (Glaz and Kang, 2008; Hailemariam, 2022) or agricultural practices (Mirzawan et al., 1994). Studies that performed thorough statistical analyses of interactions showed consistently, with a possible exception of one particular case, that both GL and GC effects were significant for all characteristics considered (Parfitt, 2000). Furthermore, GL interactions were more significant in these findings than GC interactions. The results of this analysis showed that for all characteristics, the genetic variance (G) was larger than each variance component of the interactions (GL, GC and GLC). In more detail, the GC interaction highlights the significance of genotype performance volatility across crop years, which is related to their ratooning ability, while the GLC interaction highlights the influence of location on genotype ratooning ability. The GL interaction specifically reflects the mean magnitude of changes in genotype rankings across locations. Testing genotypes across sites is more significant than testing for ratooning ability for all qualities, as shown by the finding that the GL interaction was more significant than the GC interaction. Additionally, a GLC that was much greater than GC was created by cane yield and CCS (Guilly et al., 2017). This demonstrates the relative complexity of selecting for these qualities, which must be evaluated at each location and shows that genotypic ability to ratoon is site-specific. Contrarily, the value of the GLC component for sugar yield shows that there is an indication of consistency in the evolution of sugar production throughout crop years across different locations. This may result in no changes in the relative ranking of genotypes across sites and crop years in trials when the data for the same number of cultivars are analyzed, but with a decrease in location from 22 to 16 and an increase in the number of crop years from 2 to 3 at 23%, this may complicate the identification of superior cultivars by confusing the determination of true genetic values. The majority of Thailand's areas are able to maintain ratoon crops for 1 yr. The current experiment's locations cannot be relied upon to determine their ability to ratoon due to rainfed and especially sandy soil. Since then, production has been trending downward because of prolonged droughts and an adjustment in agricultural practices for more profitable crops. By integrating more effective varieties, sugarcane breeding has significantly enhanced cane yield. The most popular of these cultivars is KK3, which currently contributes to more than 85% of Thailand's sugarcane production. Current breeding programs have mainly concentrated on cane yield and sugar content with an increasing emphasis on environmental adaptability (such as sandy soil, clay soil, drought conditions), ratooning ability and suitability (Khumla et al., 2021). This has occurred to continue improving the productivity and sustainability of the Thailand sugar industry.

Therefore, for multi-environment testing, the emphasis on GL was important. Because of the testing budget's current constraints, fewer sites or crop years must be used. Due to the increased variance component of GL being larger than GC and the strong association between two and three crop classes of all characteristics in the present experiment, increasing sites and decreasing the number of crop years was the most appropriate course of strategy. However, there has to be a sufficient number of testing locations for assessing variation. At each of the seven stations in the previous selection stage, 5–10 genotypes tended to be superior compared to local controls. Due to limitations in land resources and funding, not all of these superior varieties can be investigated worldwide. Making a decision between several potentially elite genotypes when selecting material for MET testing was always challenging (Guilly et al., 2017).

G E interactions may alter the relative ranking of genotypes across sites and crop years in trials and complicate the assessment of genuine genetic values, making it more difficult to identify superior cultivars. To evaluate the consequences of selection approaches and to play a role in improving resource allocation across places and years, it was important to thoroughly analyze the statistical significance and specific aspects of G E interactions when those were available. The contribution to the GE interaction was smaller and the plant material was more stable with a lower IPCA1 value (in absolute value). A genotype with high yields and IPCA1 scores close to zero was optimal. Low yields and low stability were characteristics of an unfavorable genotype (Ferreira et al., 2006). Between cycles, an improvement in performance occurred for some clones. A possible reason why the control's performance increased was that it had poor germination in the first year of background culturing, which was compensated for by high ratoon sprouting. The exploration of the GE interaction in distinct cycles was justified considering the sort of instability that was identified for specific clones between the cycles in the present study. Based on these findings, the analysis of AMMI2 could be explained visually. Agronomic zoning may be achieved by selecting groupings of genotypes and conditions that reside close to and in the same region of the graph (Ferreira et al., 2006). The visuals illustrated both the ideal genotype-environment combinations in terms of specific adaptability and the genotypes and environments that least contributed to the interaction (lower absolute value scores and more stable). In addition, they captured the pattern portion of the GE interaction. According to Gauch and Zobel (1997), AMMI2 may recognize genotypes with wide adaptation or recognize uniform macro environments. Ratoon usually displays higher genotype and environmental stability than plant cane. Because genotypic effects (where the GE interaction is zero) determine categorization in a stable environment, the order of the genotypes was more trustworthy (Pacheco et al., 2005). It was able to predict the final phenotypic responses of each genotype for plant and ratoon cane in a particular environment by combining estimates of the main effects with estimates of the interaction indicated by the standard AMMI2.

The GGE and AMMI biplot procedures have the capability to assess the relative importance of the environments, genotypes and G E interaction by utilizing a stability value that incorporates both cane and sugar yield across all environments. The significance of cane and sugar yield trials in the selection, assessment and recommendation of crop varieties is underscored by the thorough examination and analysis of G E under diverse environmental conditions. Stability assessments, the AMMI model and the GGE biplot approach have proven to be advantageous in identifying optimal genotypes across several settings. The AMMI techniques are widely applied in breeding projects for highly cultivated crops, including rice, maize, wheat and sugar beet. Similarly, the research conducted by Mehareb et al. (2022) revealed that experiments conducted in Egypt demonstrated the considerable importance of using five clones to effectively lead the process of selecting and recommending superior sugarcane varieties. Furthermore, these trials have proven to be essential in achieving more consistent and reliable production of both a high sugar content and cane yield. These findings were accurately anticipated by utilizing the GGE and AMMI biplot models.

The environment was the most important variable influencing changes in cane yield, sugar production and CCS. Given that the locations were chosen to represent all of the country's growth conditions, along with differences in geography, soil type, temperature, rainfall and irrigation, the substantial difference caused by location was not remarkable. It would be challenging to choose superior genotypes, due to the crop's performance being complicated by the strong interaction effects. The first and second IPCAs (which account for 67.2% and 12.8%, respectively, of the overall variance in sugar yield) have been divided among the observed G E interactions in the AMMI biplot. This was in agreement with Mattos et al. (2013) and Regis et al. (2018), who proposed that the first principal component of analysis should include the GEI pattern. However, the value was less than what Guerra et al. (2009) and Verissimo et al. (2012) observed after using AMMI analysis on sugarcane. Therefore, it is advantageous to have genotypes that are more similar to the ideal genotype. G8, G6 and G7 (check variety) were the best genotypes for more accurate producing capacity and stability, followed by G5. In addition, the present results indicated that genotypes Kps01-12 and KK3 seemed to be the most productive regarding cane and sugar production, while also being stable and adaptable. As well as enhancing ratooning ability, LK92-11 and TBy28-0348 demonstrated specific adaptation to favorable conditions, such as high soil fertility and irrigation.

Conclusions

The environment had a more significant impact on the increased variation than crop years, considering the potential of the region and the seasonality of cane yields based on distinct soil characteristics. However, weather, rainfall and cultivar capacity for ratooning all had an impact on cane production throughout crop years. The selection of the test area and the correct strategy depend on the development goals. In contrast to the quantitative data on cane yield, which should be focused on expanded locations, the focus for the qualitative data of CCS should be on growth in the number of crop year. Reducing the number of crop years was the optimum decision due to the greater variance component for GL than GC and the significant relationship between two and three crop classes for all characteristics in this experiment.

Sugarcane genotypes with stable and high yields may be chosen simply according to the graphs in the AMMI and GGE biplots. It was possible to minimize and optimize resources by reducing the number of regional trials by removing those associated with one another through indirect selection among locations. Kps01-12, KK3, LK92-11 and TBy28-0348 were the general adaptation cultivars that could grow and produce high cane and sugar yields. For METs in Thailand, these three cultivars had great promise for stability and adaptation regarding cane production, sugar yield and CCS. These genotypes could be used as alternative genetic resources for a subsequent breeding effort and should be appealing options for agricultural practices to increase yields.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The Thailand Coordinated Multi-Environment Trails of Elite Sugarcane Genotypes effort provided the data used in this investigation. The National Science and Technology Development Agency (NSTDA) and Thai Sugar Millers Corporation Limited (TSMC) collaborated to support this research through the grants FDA-CO-2558-102-TH and FDA-CO-2559-2256-TH. The Ministry of Agriculture and Cooperatives Department of Agriculture, the Office of the Cane and Sugar Board, Kasetsart University, Bangkok, Thailand and the Mitr Phol Innovation and Research Center performed the experiments and offered additional facilities. The Northeast of Thailand Cane and Sugar Research Center (NECS) and the Fundamental Fund (65A103000128) of Khon Kaen University partially funded the research.

References

Chatwachirawong, P., Boonseng, O., Summatraya, A. 1999. The effect of genotypes and GE interaction on starch content of cassava. Kasetsart J. (Nat. Sci.). 33: 171–177.

Costa, T.H.F., Masarin, F., Bonifacio, T.O., Milagres, A.M.F., Ferraz, A. 2013. The enzymatic recalcitrance of internodes of sugar cane hybrids with contrasting lignin contents. Ind. Crops Prod. 51: 202–211. doi.org/10.1016/j.indcrop.2013.08.078

Dehghani, H., Ebadi, A., Yousefi, A. 2006. Biplot analysis of genotype by environment interaction for barley yield in Iran. Agron. J. 98: 388–393. doi.org/10.2134/agronj2004.0310

Dlamini, N.E., Ramburan, S. 2016. Investigating sugarcane genotype × environment interactions in the Northern area of the Swaziland sugar industry using variance components and biplot analysis. Proc. S. Afr. Sug. Technol. Ass. 89: 234–257.

Eberhart, S.A., Russell, W.A. 1966. Stability parameters for comparing varieties. Crop Sci. 6: 36–40. doi.org/10.2135/cropsci1966.0011183X000600010011x

Ferreira, D.F., Demetrio, C.G.B., Manly, B.F.J., Machado, A.A., Vencovsky, R. 2006. Statistical models in agriculture: Biometrical methods for evaluating phenotypic stability in plant breeding. Cerne. Lavras. 12: 373–388.

Gauch, H.G. 1988. Model selection and validation for yield trials with interaction. Biometrics 44: 705–715. doi.org/10.2307/2531585

Gauch, H.G., Zobel, R.W. 1997. Identifying mega-environments and targeting genotypes. Crop Sci. 37: 311–326. doi.org/10.2135/cropsci1997.0011183X003700020002x

Glaz, B., Kang, M.S. 2008. Location contributions determined via GGE biplot analysis of multi environment sugarcane genotype-performance trials. Crop Sci. 48: 941–950. doi.org/10.2135/cropsci2007.06.0315

Guerra, E.P., Oliveira, R.A., Daros, E., Zambon, J.L.C., Ido, O.T., Bespalhok Filho, J.C. 2009. Stability and adaptability of early-maturing sugarcane clones by AMMI analysis. Crop Breed. Appl. Biotechnol. 9: 260–267.

Guilly, S., Dumont, T., Thong-Chane, A., Barau, L., Hoarau, J.Y. 2017. Analysis of multi environment trials (MET) in the sugarcane breeding program of Reunion Island. Euphytica 213: 213. doi.org/10.1007/s10681-017-1994-1

Hailemariam, H.M. 2022. Adaptability and stability for soybean yield by AMMI and GGE models in Ethiopia. Front. Plant Sci. 13: 950992. doi.org/10.3389/fpls.2022.950992

Kaya, Y., Akcura, M, Taner, S. 2006. GGE-biplot analysis of multi-environment yield trials in bread wheat. Turk. J. Agric. For. 30: 325–337.

Khan, I.A, Seema, N., Raza, S., Yasmine, S., Bibi, S. 2013. Environmental interactions of sugarcane genotypes and yield stability analysis of sugarcane. Pak. J. Bot. 45: 1617–1622.

Khruengpatee, J., Jaisil, P., Jongrungklang, N., Songsri, P. 2023. Identification of effective test sites represented to mega-environment for sugarcane breeding programs in Thailand. Asian J. Plant Sci. 22: 547–557. doi.org/10.3923/ajps.2023.547.557

Khumla, N., Sakuanrungsirikul, S., Punpee, P., Hamarn, T., Chaisan, T., Soulard, L., Songsri, P. 2021. Sugarcane breeding, germplasm development and supporting genetics research in Thailand. Sugar Tech. 24: 193–209. doi.org/10.1007/s12355-021-00996-2

Kimbeng, C.A., Zhou, M.M., Da Silva, J.A. 2009. Genotype × environment interactions and resource allocation in sugarcane yield trials in the Rio Grande Valley Region of Texas. J. Am. Soc. Sugarcane Tech. 29: 11–24.

Klomsa-ard, P. Jaisil, P., Patanothai, A. 2013. Performance and stability for yield and component traits of elite sugarcane genotypes across production environments in Thailand. Sugar Tech. 15: 354–364. doi.org/10.1007/s12355-013-0215-z

Kusangaya, S., Warburton, M.L., van Garderen, E.A., Jewitt, G.P.W. 2014. Impacts of climate change on water resources in southern Africa: A review Phys. Chem. Earth. 67: 47–54. doi.org/10.1016/j.pce.2013.09.014

Mattos, P.H.C., Oliveira, R.A., Bespalhok, F.J.C., Daros, E., Verissimo, M.A.A. 2013. Evaluation of sugarcane genotypes and production environments in Parana by GGE biplot and AMMI analysis. Crop Breed. Appl. Biotechnol. 13: 83–90. doi.org/10.1590/S1984-70332013000100010

Mehareb, E.M., Osman, M.A.M., Attia, A.E., Bekheet, M.A., Abo Elenen, F.F.M. 2022. Stability assessment for selection of elite sugarcane clones across multi-environment based on AMMI and GGE-biplot models. Euphytica 218: 95. doi.org/10.1007/s10681-022-03025-9

Mirzawan, P.D.N, Cooper, M., De Lacy, I.H., Hogarth, D.M. 1994. Retrospective analysis of the relationships among the test environments of the southern Queensland sugarcane breeding programme. Theor. Appl. Genet. 88: 707–716. doi.org/10.1007/BF01253974

Natarajan, S., Basnayake, J., Lakshmanan, P., Fukai, S. 2020. Limited contribution of water availability in genotype-by-environment interaction in sugarcane yield and yield components. J. Agron. Crop Sci. 206: 665–678. doi.org/10.1111/jac.12407

Pacheco, R.M., Duarte, J.B., Vencovsky, R., Pinheiro, J.B., Oliveira, A.B. 2005. Use of supplementary genotypes in AMMI analysis. Theor. Appl. Genet. 110: 812–818. doi.org/10.1007/s00122-004-1822-6

Parfitt, R.C. 2000. Genotype × environment interaction among secondary variety trials in the northern region of the South African sugar industry. Proc. S. Afr. Sug. Technol. Ass. 74: 245–248.

Parfitt, R.C., Thomas, D.W. 2001. Final stage transfers in a regional breeding and selection programme for sugarcane. Proc. S. Afr. Sug. Technol. Ass. 75: 151–153.

Pobkhunthod, N., Authapun, J., Chotchutima, S., Rungmekarat, S., Kittipadakul, P., Duangpatra, J., Chaisan, T. 2022. Multilocation yield trials and yield stability evaluation by GGE biplot analysis of promising large-seeded peanut lines. Front. Genet. 13: 876763. doi.org/10.3389/fgene.2022.876763

Ramburan, S., Nxumalo, N. 2017. Regional, seasonal, cultivar and crop-year effects on sugarcane responses to residue mulching. Field Crops Res. 210: 136–146. doi.org/10.1016/j.fcr.2017.06.001

Rashidi, M., Farshadfar, E., Jowkar, M.M. 2013. AMMI analysis of phenotypic stability in chickpea genotypes over stress and non-stress environments. Intl. J. Agri. Crop. Sci. 5: 253–260.

R Core Team. 2010. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/, 18 August 2023.

Rea, R., Suosa-Vieira, O., Diaz, A., Ramon, M., Briceno, R., George, J., Nino, M. Balzano-Nogueira, L. 2016. Genotype–environment Interaction, mega environments and two-table coupling methods for sugarcane yield studies in Venezuela. Sugar Tech. 18: 354–364. doi.org/10.1007/s12355-015-0407-9

Rea, R., Suosa-Vieira, O., Ramon, M., Alejos, G., Diaz, A., Briceno, R. 2011. AMMI analysis and its application to sugarcane regional trials in Venezuela. Sugar Tech. 13: 108–113. doi.org/10.1007/s12355-011-0070-8

Regis, J.A.V.B., Andrade, J.A.C., Santos, A., Moraes, A., Trindade, R.W.R., Henriques, H.J.R. Oliveira, L.C. 2018. Adaptability and phenotypic stability of sugarcane clones. Pesq. Agropec. Bras. 53: 42–52. doi.org/10.1590/S0100-204X2018000100005

Serivichayaswadi, P., Sirasoontorn, S., Chatwachirawong, P. 1997. Yield and yield components relationship in sugarcane. Kasetsart J. (Nat. Sci.) 31: 20–27.

Tarakanovas, P., Ruzgas, V. 2006. Additive main effect and multiplicative interaction analysis of grain yield of wheat varieties in Lithuania. Agron. Res. 4: 91–98.

Tena, E., Goshu, F., Mohamad, H., Tesfa, M., Tesfaye, D., Seife, A. 2019. Genotype × environment interaction by AMMI and GGE-biplot analysis for sugar yield in three crop cycles of sugarcane (*Saccharum officinirum* L.) clones in Ethiopia. Cogent Food Agric. 5: 1651925. doi.org/10.1080/23311932.2019.1651925

Tiawari, D.K., Pandey, P., Singh, R.K., Singh, S.P., Singh, S.B. 2011. Genotypes × environment interaction and stability analysis in elite clones of sugarcane (*Saccharum officinarum* L.). Int. J. Plant Breed. Genet. 5: 93–98. doi.org/10.3923/ijpbg.2011.93.98

Verissimo, M.A.A., Silva, D.A.S., Aires, R.F., Daros, E., Panziera, W. 2012. Adaptability and stability of early sugarcane genotypes in Rio Grande do Sul, Brazil. Agric. Res. Brazil. 47: 561–568. doi.org/10.1590/S0100-204X2012000400012

Yan, W., Holland, J.B. 2010. A heritability-adjusted GGE biplot for test environment evaluation. Euphytica 171: 355–369. doi.org/10.1007/s10681-009-0030-5

Yan, W., Kang, M.S., Ma, B., Woods, S., Cornelius, P.L. 2007. GGE biplot vs AMMI analysis of genotype-by-environment data. Crop Sci. 47: 643–655. doi.org/10.2135/cropsci2006.06.0374

Zobel, R.W., Wright, M.J., Gauch, H.G. 1988. Statistical analysis of yield trial. Agron. J. 80: 388–393. doi.org/10.2134/agronj1988.00021962008000030002x