International Journal of Agricultural Technology 2025 Vol. 21(6):2261-2274
DOI: https://doi.org/10.63369/ijat.2025.21.6.2261-2274
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

Evaluation of ear yield stability of organic sweet corn hybrids at different elevations in the humid tropical climate of Indonesia

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Chozin, M., Sudjatmiko, S. and Fahrurrozi, F. (2025). Evaluation of ear yield stability of organic sweet corn hybrids at different elevations in the humid tropical climate of Indonesia. International Journal of Agricultural Technology 21(6):2261-2274.

Abstract Yield trials are an important step in a breeding program to evaluate the performance of selected genotypes under various environments. In this study, the ear yield stability and adaptability of ten experimental sweet corn hybrids bred for organic production was estimated using the AMMI model. The combined analysis of variance indicated that the location effect (E) was a primary source of variation in ear yield (35%), followed by hybrid (G) and hybrid-location interaction (GEI) effects, which accounted for 27% and 16%, respectively. Among the tested locations, highland was identified as the most productive environment. However, the significant GEI effect suggests a possible inconsistency in the ear yield among the hybrids across elevations. Both the estimates of AMMI stability value (ASV) and yield stability index (YSI) indicate that the experimental hybrid from the cross of Caps-5 x Caps-22, as followed by check of commercial hybrid Paragon, could serve as the most suitable hybrids for organically growing sweet corn under different elevation in the humid tropical climate of Indonesia.

Keywords: AMMI stability value, Combined analysis of variance, Principal component, Unhusked ear yield, Yield stability index

Introduction

Sweet corn is not Indonesian crop by origin, but its popularity has grown since it was commercially produced in the 1980s. Although there is no readily available data for the harvest area and annual production of sweet corn, the crop is widely grown throughout the country. It can be easily grown in field corn-producing areas. However, unlike field corn, which is harvested when the kernels are fully mature, sweet corn is harvested in the immature kernel stage and is sold primarily in the fresh market as unhusked ear. Growing sweet corn can be economically more profitable than field corn due to the high unit price of the ears and earlier harvest (Dyah and Kahfi, 2021). Additionally, the remained stover following harvest can be utilized as a high-quality hay or silage for animal feed (Bakshi *et al*., 2016).

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The growing demand for sweet corn, coupled with increasing awareness of health and environmental issues in crop production, has led to the development of sweet corn varieties for organic production. The rationale is that not all available varieties addressed for conventional production may perform well in organic environments (Ardelean *et al*., 2012; Woodruff *et al.*, 2019; Kara and Oygur, 2020). Similar issues were also reported on other crops (Kazimierczak *et al*., 2019; Guilherme *et al*., 2020; Rodríguez-Ortiz *et al*., 2022). Unlike conventional systems, organic crop production is characterized by the absence of the use of synthetic pesticides, fertilizers, or genetically modified seeds. In this case, crop productivity will be dependent on crop rotation, animal manure, organic waste, and biological pest management (Mahanta *et al*., 2021).

In Indonesia, sweet corn is grown at different elevations, from coastland to highland, and as a tropical country, there is a close relationship between elevation and climate, especially air temperature. The mean air temperature decreases by 0.65 °C for every 100 m increase in elevation (Juo and Franzluebbers, 2003) and it has been reported that sweet corn is sensitive to atmospheric temperature (Morton *et al*., 2017; Dhaliwal and Williams, 2022). Furthermore, there is a difference in temperature sensitivity among sweet corn hybrids as grown at different elevations (Ruswandi *et al*., 2020), indicating the importance of genotype-environment interaction (GEI) effect on crop performance. The presence of such GEI effect virtually gives a message to the organic sweet corn breeder that the developed hybrids for tropical region could perform inconsistently across elevations and, hence, encourages the breeder to evaluate the stability of the hybrids' performance over elevations and determine the adaptability of the hybrids for a particular elevation.

A multi-environment test (MET) is a standard procedure for evaluating genotypes' performance over different environments. The goals are to identify best-performing genotypes in different environments (stability) and the best genotypes for specific environment (adaptability). There are several statistical methods, both parametric (univariate and multivariate) and non-parametric, used for determination of the genotype's stability and adaptability in presence of GEI effect (Fasahat *et al*., 2015). Among them is AMMI model (additive main effects and multiplicative interaction) that combines analysis of variance and principal component analysis (Sharifi *et al*., 2017). The AMMI model is robust in dealing with the unbalanced data (Bernardo Júnior *et al*., 2018) and particularly useful in visualizing GEI pattern, stability, and adaptability (Rao *et al*., 2022). The present study was addressed to employ the AMMI model for estimating the ear yield stability of 10 experimental sweet corn hybrids bred for organic production as grown at different elevations of a humid tropical climate and determining the elevations best suited for the ear yield production of given hybrids.

Materials and methods

Experimental sites

The study was carried out from July to October 2024 at three locations differing in elevations in the humid tropic of Bengkulu Province, Indonesia. The weather conditions during the growing season at each location are presented in Table 1.

Table 1. Mean daily temperature, mean daily relative humidity, and monthly rainfall during the growing season at each location

Location	Elevation (m asl)	Mean daily tempera-ture (°C)	Mean daily relative humidiy (%)	Monthly rainfall (mm)
Coastland (City of Bengkulu)	10	26.8	84.1	288.5
Midland (Kepahiang Regency)	600	25.2	76.9	275.5
Highland (Rejang Lebong Regency)	1050	21.9	82.9	306.9

Planting materials

Ten experimental hybrids bred for organic production were chosen from half-diallel crossings of eight advanced inbred lines of sweet corn as the planting materials for the study. These were Caps-2 x Caps-17A (G1), Caps-3 x Caps-17A (G2), Caps-3 x Caps-17B (G3), Caps-5 x Caps-17B (G4), Caps-5 x Caps-22 (G5), Caps-15 x Caps-22 (G6), Caps-17A x Caps-17B (G7), Caps-17A x Caps-22 (G8), Caps-17B x Caps-23 (G9), and Caps 22 x Caps 23 (G10). In addition, two commercial hybrids, Bonanza (G11) and Paragon (G12), were included as check varieties.

Experimental design and crop management

At each location, all the genetic materials were allotted on the experimental plots according to a randomized complete block design (RCBD) involving three replications. Each plot consisted of 5-m-long double rows with 75-cm row spacing and 25-cm plant spacing. Cow manure at 5 t/ha was amended on each plot a week before planting and supplemental basal side dressing fertilizers using locally made liquid organic fertilizer (Fahrurrozi *et al*., 2022) was applied as foliar spray at 2, 3, 4, 5, 6, 7 and 8 weeks after planting. Insect pests, diseases, and weeds were controlled without the use of agrochemical products. Harvest of ear was carried out as the kernel reached the early dough stage. The ear yield data were collected as weight of unhusked ear per plot and, then, converted to hectare.

Data analysis

A combined analysis of variance across environments was applied to ear yield data collected from the three locations in order to assess the importance of genotypes (G), environments (E), and the genotype-environment interaction (GEI) effects. Proc GLM of SAS V9.4 (SAS Institute Inc., Cary, NC) was used to run the analysis predicated on the model below.

$$Y_{ijk} = \mu + G_i + E_j + B_{k(j)} + (GE)_{ij} + \varepsilon_{ijk}$$

Where Y_{ijk} is the observed value of the i^{th} genotype at j^{th} environment and k^{th} block within the j^{th} environment; μ is the grand mean; G_i is the i^{th} genotype effect; E_j is the j^{th} environment effect; $B_{k(j)}$ is the k^{th} block effect in the j^{th} environment; $(GE)_{ij}$ is the interaction effect of the i^{th} genotype and the j^{th} environment; and i^{jk} is the experimental error.

The following AMMI model (Zobel *et al.,* 1988) was used to analyze the pattern of GEI effect and the analysis was performed using PBTools v1.4 (available at http://bbi.irri.org/ products). The generated biplots were used for the graphical interpretation of the GEI effect.

$$\hat{Y}_{ij} = \mu + G_i + E_j + \sum_{1}^{k} \lambda_k \alpha_{ik} \gamma_{jk} + \varepsilon_{ij}$$

where Y_{ij} is the expected value of the i^{th} genotype in the j^{th} environment; μ is the grand mean; G_i is the i^{th} genotype effect; E_j is the j^{th} environment effect; λ_k, $_{ik}$, and γ_{jk} are singular value, genotype eigenvectors, and environment eigenvectors for the principal components (PCA), respectively; and ε_{ij} is the residual associated with i^{th} genotype and j^{th} environment.

AMMI's stability value (ASV) and yield stability index (YSI) for selecting genotypes with higher yield stability and the mean yield over the environments, respectively, were calculated using the following equations, as described by Bose *et al*. (2014).

$$ASV = \sqrt{\left[\frac{\text{SS IPC1}}{\text{SS IPC2}} (\text{IPC1}_{\text{score}}) \right]^2 + (\text{IPC2}_{\text{score}})^2}$$

where SS is sum of squares, IPC1 and IPC2 are the first and second PCA of interaction, respectively.

$$YSI = RASV + RY$$

where RASV is the rank of the AMMI stability value of the genotype and RY is the rank of the mean yield of genotypes (RY) across environments. The genotypes with the lowest YSI values are considered the most stable with high mean yield.

Results

Mean ear yield

The mean ear yield of the hybrids tested at different locations is seen in Table 2. Among all the sites, the ear yield in the upland environment was the highest (24.84 tons/ha), followed by the midland environment (21.06 tons/ha), and the ear yield in the coastal environment was the lowest (20.84 t/ha) The coefficient of variation (CV) indicated that the degree of variability of the hybrids in each environment was comparably low (< 10%). Nevertheless, the inconsistency of the hybrids is found to be notable from their ranking changes across environments.

Table 2. Mean ear yield (t/ha) and rank order of 12 sweetcorn hybrids organically grown at three locations differing in elevation

Hybrid	Hybrid Code	Coastland (E1)	Rank	Midland (E2)	Rank	Highland (E3)	Rank
Caps-2 x Caps-17A	G1	20.86	6	22.60	4	24.77	6
Caps-3 x Caps-17A	G2	17.57	12	17.13	12	20.76	12
Caps-3 x Caps-17B	G3	21.99	4	20.07	8	23.73	9
Caps 5 x Caps 17B	G4	20.65	6	22.09	4	26.76	2
Caps-5 x Caps-22	G5	22.97	2	23.43	2	28.61	1
Caps-15 X Caps-22	G6	19.05	8	19.91	6	25.42	3
Caps-17A x Caps-17B	G7	20.93	5	23.79	1	24.63	4
Caps-17A x Caps-22	G8	20.17	8	21.98	2	26.44	1
Caps-17B x Caps-23	G9	18.94	9	19.30	5	23.26	5
Caps-22 x Caps-23	G10	20.23	9	19.32	4	23.69	4
Bonanza	G11	23.96	2	20.47	3	24.30	3
Paragon	G12	22.72	6	22.65	1	25.67	1
Mean		20.84		21.06		24.84	
CV (%)		8.86		9.51		8.00	

Analysis of variance

The performed combined analysis of variance revealed that the effects of location (E), hybrid (G), and location-hybrid interaction (GEI) had significant role on ear yield (Table 3). These three effects captured 81.58% of the total sum of square. Moreover, principal component analysis using the AMMI model showed that the GEI effect can be partitioned into two IPCs, i.e., IPC1 and IPC2, which accounted for 71.05% and 28.95% of the GE interaction sum of squares, respectively.

Table 3. Analysis of variance and partitioning GEI effect by AMMI analysis for ear yield of 12 sweetcorn hybrids organically grown at three locations differing in elevation

Source of variation	df	SS	MS	F Value	% SS_{total}	% SS_{GEI}
Location (E)	2	367.99	183.99	84.47**	34.15	
Block/Location	6	54.70	9.17	4.19**	5.08	
Hybrid (G)	11	419.79	38.16	17.52**	38.96	
Location*Hybrid (GEI)	22	91.24	4.15	1.90*	8.47	
IPC1	12	64.83	5.40	2.08*		71.05
IPC2	10	26.41	2.64	1.02		28.95
Error	66	143.76	2.18		13.34	
Total	107	1077.49				

*, ** represent significance at $P < 0.05$ and $P < 0.01$ by F test, respectively

AMMI-1 biplot

The graph of the AMMI-1 biplot, shown in Figure 1, plots the associated mean ear yield as the abscissa (x-axis) and IPC1 scores as the ordinate (y-axis). This plot helps interpret the relationship between the additive main effects (E and G) and the interaction effect of GE. Displacements of location and hybrid along the abscissa reveal changes in the main effects, whereas displacements along the ordinate indicate differences in the interaction effects. In these circumstances, the main effect is related to the productivity, while the interaction effect is related to the predictability of the location or the stability of the hybrid. The dashed vertical line that bisects the horizontal axis represents the grand mean of ear yield. The locations or hybrids situated to the right side outperformed this mean. On the other hand, the dashed horizontal line that divided the vertical axis corresponds to the zero line for IPC1. The closer a location or a hybrid to this line showed the more predictable the location and the more stable the hybrid, respectively.

The graphical representation of the tested sites indicated that each of the three locations possesses distinct characteristics. E1 is situated in the upper middle left of quadrant IV, implying that the coastal environment exhibited lower productivity and less predictable. E2 is located in the lower middle left of quadrant III, suggesting that the midland environment was similarly less productive, but it had a greater degree of predictability. Finally, E3 is represented in the lower middle right of quadrant II, signifying that the highland environment was the most productive and, to a certain extent, predictable. Following the same idea, G12, G5, G4, G7, G8, G1, and G11 occupying quadrants I and II can be classified as productive hybrids with moderate to good stability, except for G11 due to its lack of stability. The remaining hybrids left in quadrant III or quadrant IV can be categorized as being less productive with moderate to good stability.

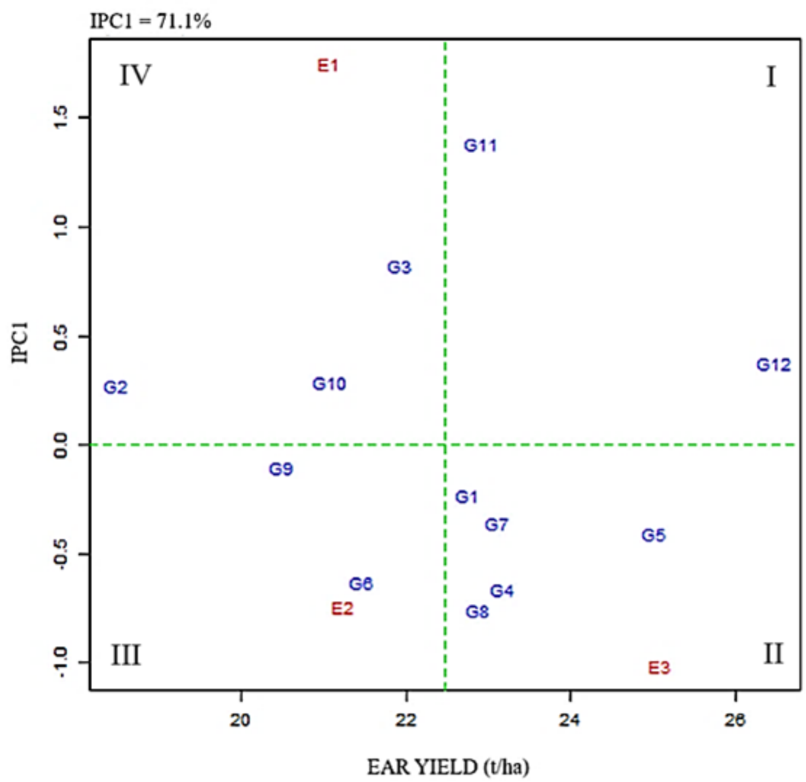

Figure 1. AMMI-1 biplot of 12 sweetcorn hybrids organically grown at three locations differing in elevation

AMMI-2 biplot

The AMMI-2 biplot is displayed IPC1 and IPC2 positioned along the x-axis and y-axis, respectively as illustrated in Figure 2. This arrangement facilitated the assessment of each location's contribution to GEI effect and allowed for the analysis of the varying responses of hybrids across different locations. The graph is connected the spokes of each location's IPC to the origin, with the length of each spoke representing the intensity of the location's influence on the interactive force. It is noteworthy that the spokes of the three locations exhibited similar lengths, suggesting a comparable interactive force. Furthermore, hybrids plotted nearer to the origin had greater stability, whereas those plotted more distantly tended to be less stable. Hybrids placed closer to a specific location’s spoke would have higher adaptability to that environment, while those further away from the spoke that reduced adaptability to the same environmental conditions. Consequently, G9, G2, G12, and G10 emerged as the stable hybrid across locations. On the other hand, G3 and G11 showed superior adaptation to the coastland (E1), while G1 and G7 to the midland (E2). The remaining hybrids, specifically G4, G5, G6, and G8 showed excellent adaptation to the highland (E3).

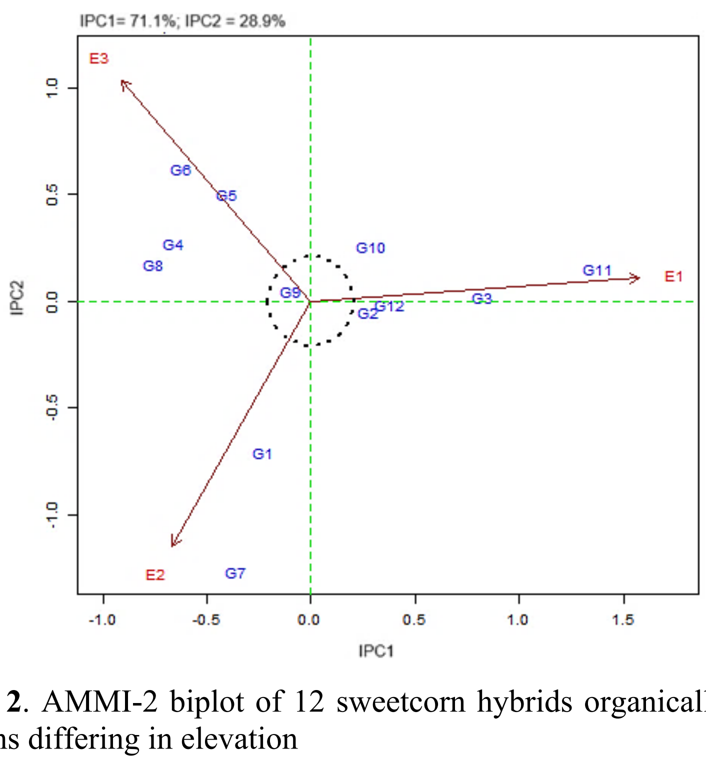

Figure 2. AMMI-2 biplot of 12 sweetcorn hybrids organically grown at three locations differing in elevation

AMMI stability value and yield stability index

The mean ear yield, IPC1 and IPC2 scores, AMMI stability value (ASV) and yield stability index (YSI) for every hybrid at the three locations are listed in Table 4. The mean ear yield ranged from 18.49 t/ha to 25.00 t/ha, leading to an overall mean yield of 22.25 t/ha. Notably, three hybrids—G3, G4, G5, and G7—achieved higher ear yields than those of the lower check variety (G11). However, it is important to highlight that only hybrid G5 exceeded the yield of the higher check variety (G12).

The scores associated with IPC1 and IPC2 reflected the relative positioning of the hybrids along the respective axes in the AMMI-2 biplot. The ASVs denoted the Pythagorean distances of the hybrids from the origin of the IPC1 and IPC2 coordinate planes. The ASV estimated for the hybrids varied from 0.052 to 10.762, arranged in ascending order. The hybrid exhibiting the minimum ASV values is classified as highly stable. Notably, G9 and G2 demonstrated the smallest ASVs, securing the top two positions in terms of yield stability. The YSI value incorporated both measurements for the hybrid stability and ear yield performance in a single criterion. The lower YSI indicated greater stability and higher yield. As a result, G5 and G12 can be recognized as the most optimal hybrids for a wider range of environments by taking into account their productivity levels and stability.

Table 4. Mean ear yield, IPC scores, AMMI stability value, and yield stability index of twelve sweetcorn hybrids grown organically at three locations differing in elevation

Hybrid code	Mean ear yield (t/ha)	IPC1 score	IPC2 score	ASV	ASV rank	YSI
G1	22.74	-0.209	-0.690	0.719	5	12
G2	18.49	0.284	-0.019	0.448	2	14
G3	21.93	0.836	0.071	3.882	11	19
G4	23.17	-0.663	0.272	2.510	8	11
G5	25.00	-0.408	0.514	1.186	6	7
G6	21.46	-0.633	0.624	2.607	9	18
G7	23.12	-0.331	-1.250	2.169	7	11
G8	22.86	-0.753	0.173	3.171	10	16
G9	20.50	-0.092	0.068	0.052	1	12
G10	21.08	0.294	0.287	0.561	4	14
G11	22.91	1.390	0.217	10.762	12	17
G12	23.68	0.283	-0.267	0.516	3	5

Discussion

In a plant breeding program, conducting multi-environment trials (MET) can assist in evaluating the stability and adaptability of breeding materials, aiding in selecting which genotypes to advance and establishing the identity of new cultivars with specific and general adaptation as they are disseminated (Pour-Aboughadareh *et al*., 2022). The present MET study showed that the ear yield of sweet corn hybrids grown organically fluctuated across locations differing in elevations. A closer inspection of the table reveals the presence of variability in ear yield among the hybrids at each site. The fluctuations in the ranking of hybrids across different locations imply that the genotypes exhibited inconsistent responses in varying environments (Crossa, 1990). This perspective is also reflected in the combined analysis of variance, where the genotype-environment interaction (GEI) effect on ear yield performance is notably significant. Similar findings are also reported by other workers (Zystro *et al*., 2021; Patel *et al*., 2023)

An additional examination utilizing the AMMI model suggested by Gauch (1992) has identified the GEI effect can be decomposed into two interaction principal component axes (IPCAs) that collectively explain the entire GEI sum of square. The AMMI model also offers graphical interpretative tools to help understand complex genotype-environment interactions commonly found in a yield trial (Gauch, 2013). The AMMI-1 graph visualizing the interrelationships between genotypes and environment serves to highlight coastland (E1) as a less productive and unpredictable area for ear yield, midland (E2) as less productive but predictable for ear yield, and highland (E3) as a productive and predictable area for ear yield. The graph also facilitated discernment of the ear yield productivity and stability of the tested hybrids, where G12, G5, G4, G7, G8, and G1 represent productive hybrids with moderate to good stability, G11 is found to be a productive hybrid but less stable, and G3, G6, G10, G9, and G2 were less productive but good in stability. The AMMI-2 graph would be further helped in elucidating the hybrid's stability and adaptability by incorporating the second IPCA to explain the interaction as well. As a result, G9, G2, G12, and G10 showed the stable hybrids across elevations. G3 and G11, on the other hand, are found to be better suited to coastal environments, G1 and G7 to midland environments, and G4, G5, G6, and G8 to highland environments.

The major drawback of AMMI-2 did not make provision for a quantitative stability measure, which is essential for quantifying and ranking the hybrids according to their yield stability. To address this issue, the AMMI stability value

(ASV) provided such a measurement. Specifically, ASV is represented the quantitative distance of the hybrids from the origin of the AMMI-2 graph, and this distance can be ranked to reflect the relative stability of the hybrids (Purchase *et al*., 2000). A hybrid with the lowest ASV score is considered the most stable; thus, G12 and G1 can be identified as the most stable hybrids. Furthermore, by providing yield stability index (YSI) for each hybrid is suggested by Kang (1993), discernment the hybrids can be made not only by their stability but also by their productivity. Given that lower YSI indicated higher yield and enhanced stability, G5 and the subsequent check hybrid (G12) become the most suitable choices for organically growing sweet corn under different environmental conditions. This finding suggested that the genotypes exhibiting the highest stability do not always correlate with optimal yield performance, as also reported by Patel *et al*. (2023).

Acknowledgements

This work was financially supported by the Directorate General of Higher Education, Ministry of Education and Culture of the Republic of Indonesia [Grant number 043/E5/PG.02.00.PL/2024].

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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(Received: 12 November 2024, Revised: 29 July 2025, Accepted: 26 August 2025)