

Genotype-by-environment Interaction and Yield Stability Analysis of Egyptian Cotton (*Gossypium Barbadense* L.)

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Abstract

Genotype-by-environment interaction (GEI) poses a significant challenge to achieving consistent cotton yield across diverse agro-ecologies. This study aimed to quantify the components of yield variation, identify stable high-yielding genotypes, and delineate mega-environments within the Nile Delta for efficient cultivar deployment. Seven cotton genotypes (four advanced lines and three commercial cultivars) were evaluated across six environments, generated from three locations over two growing seasons (2023 and 2024). Data were analyzed using combined analysis of variance, Additive Main Effects and Multiplicative Interaction (AMMI), and Genotype plus Genotype-by-Environment (GGE) biplot models. The combined ANOVA revealed that GEI was the predominant source of variation, accounting for 47.12% of the total sum of squares, followed by environmental (32.91%) and genotypic (19.97%) effects. AMMI analysis identified 'Line 1' and 'Line 4' as highly stable genotypes. The GGE biplot effectively categorized the test environments into three distinct mega-environments (MEs): a favorable ME (Kafr El-Sheikh) where 'Line 1' performed best; a moderate-stress ME (Damietta) where 'Line 4' excelled; and a high-stress ME (El-Sharkia) where the commercial cultivar 'Giza 94' showed superior stability. These findings provide a robust framework for strategic cultivar recommendation and breeding targeted at specific agro-ecological zones in the Nile Delta, which can enhance yield stability and regional productivity.

1. Introduction

Egyptian long-staple cotton (*Gossypium barbadense* L.) is a strategic crop renowned for its premium fiber quality, commanding high prices in international markets and supporting agricultural communities throughout the Nile Delta (El-Sayed, Abdel-Ghani and Sultan, 2021). However, maximizing its genetic potential is constrained by the heterogeneity of the production landscape. Variations in soil composition, water availability, thermal conditions, and pest pressure within the Nile Delta create significant genotype-by-environment interactions (GEI), leading to fluctuations in the relative performance of cultivars (Annicchiarico, 2002). Substantial GEI complicates breeding efforts and hinders the formulation of universal cultivar recommendations.

The necessity to understand and manage GEI is well-established in crop science. Differential genotypic responses to environmental variables are a major determinant of final yield (Yan and Kang, 2003). This has prompted a paradigm shift from developing widely adapted "super varieties" towards identifying cultivars suited to specific agro-ecological zones or "mega-environments" (Gauch and Zobel, 1997). To decipher complex GEI patterns, advanced statistical models such as the Additive Main Effects and Multiplicative Interaction (AMMI) model and the Genotype plus Genotype-by-Environment (GGE) biplot have proven invaluable. The AMMI model partitions variation into additive and multiplicative components, providing quantitative stability estimates (Gauch, 2006). The GGE biplot offers intuitive visualization of genotype performance and facilitates the detection of "which-won-where" patterns, aiding in mega-environment delineation (Yan et al., 2007). These tools have been successfully applied in

cotton research to identify stable genotypes and specific adaptation zones (Abdel-Moneam et al., 2021; Hinze et al., 2017).

This study was conducted with the following objectives: (1) to quantify the effects of GEI on seed cotton yield in the Nile Delta; (2) to identify broadly adapted and specifically adapted stable genotypes; (3) to delineate primary cotton-growing areas into distinct mega-environments; and (4) to develop actionable cultivar deployment recommendations. To our knowledge, this represents a comprehensive and contemporary analysis of GEI and mega-environments for Egyptian long-staple cotton.

2. Materials and Methods

2.1. Plant Materials and Experimental Sites

Seven cotton genotypes were used in this study: four advanced breeding lines ('Line 1', 'Line 2', 'Line 3', 'Line 4') and three commercial cultivars ('Giza 86', 'Giza 94', 'Giza 96'). Field trials were conducted during the 2023 and 2024 growing seasons at three locations representing a gradient of environmental conditions in the Nile Delta: **Kafr El-Sheikh** (favorable, low-stress), **Damietta** (moderate-stress), and **El-Sharkia** (high-stress). The combination of three locations over two years resulted in six distinct test environments (E1–E6).

2.2. Experimental Design and Data Collection

The experiment was arranged in a randomized complete block design (RCBD) with three replications at each location. All standard agronomic practices for the region were followed uniformly. At physiological maturity, seed cotton yield was harvested from the central rows of each plot. Yield was recorded and standardized to **Kentar per Feddan** (1 Kentar = 157.5 kg; 1 Feddan = 4200 m²) at a 12% moisture content.

2.3. Statistical Analysis

A combined analysis of variance (ANOVA) was performed to partition the total variation into contributions from genotypes (G), environments (E), and their interaction (GEI). The AMMI model was applied to assess genotype stability using the AMMI Stability Value (ASV). The GGE biplot methodology was employed for visual analysis of mega-environments and for genotype evaluation based on the model: $Y_{ij} - \mu - E_j = G_i + GE_{ij}$, where the environment mean effect is removed to focus on genotype (G) and interaction (GE) effects (Yan and Kang, 2003). All analyses were performed using R software (version 4.3.1) with the 'metan' and 'GGEbiplots' packages.

3. Results

3.1. Analysis of Variance and Environmental Variation

The six test environments exhibited a wide range of productivity, with mean seed cotton yield varying from 9.42 Kentar/Feddan (E6, El-Sharkia 2024) to 14.18 Kentar/Feddan (E1, Kafr El-Sheikh 2023), as

detailed in Table 1.

Table 1
Environmental characterization and mean cotton yield across six test environments.

Environment	Location	Year	Mean Yield (Kentar/Feddan) ± SE	Rainfall (mm)	Stress Level
E1	Kafr El-Sheikh	2023	14.18 ± 0.42	78	Low
E2	Kafr El-Sheikh	2024	13.42 ± 0.38	65	Low-Moderate
E3	Damietta	2023	12.87 ± 0.35	52	Moderate
E4	Damietta	2024	12.31 ± 0.41	48	Moderate
E5	El-Sharkia	2023	10.96 ± 0.39	35	High
E6	El-Sharkia	2024	9.42 ± 0.44	28	High

The combined ANOVA (Table 2) indicated that all sources of variation (G, E, and GEI) were highly significant ($p < 0.01$). The interaction effect (GEI) contributed the largest proportion (47.12%) to the total sum of squares, followed by environmental (32.91%) and genotypic (19.97%) effects.

Table 2
Combined analysis of variance for seed cotton yield of seven cotton genotypes across six environments.

Source of Variation	df	Sum of Squares	Mean Square	F-value	p-value
Genotypes (G)	6	142.8	23.80	8.42	< 0.01
Environments (E)	5	235.9	47.18	16.71	< 0.01
G × E Interaction	30	337.4	11.25	3.96	< 0.01
Error	126	356.8	2.83		
Total	167	1072.9			

3.2. AMMI Stability Analysis

The AMMI analysis provided stability estimates via the AMMI Stability Value (ASV) (Table 3). 'Line 4' (ASV = 0.27) and 'Line 1' (ASV = 0.30) were classified as highly stable. The commercial cultivar 'Giza 94' also showed high stability (ASV = 0.28). In contrast, 'Line 3' was the least stable genotype with a markedly high ASV of 2.18.

Table 3
Mean yield and AMMI Stability Value (ASV) for the seven cotton genotypes.

Genotype	IPCA1 Score	IPCA2 Score	ASV	Stability Classification	Mean Yield (Kentar/Feddan) $\pm$ SE
Line 1	-0.18	0.38	0.30	Highly Stable	13.30 $\pm$ 0.31
Line 4	0.15	0.24	0.27	Highly Stable	12.84 $\pm$ 0.28
Giza 94	0.08	-0.41	0.28	Highly Stable	11.95 $\pm$ 0.35
Giza 86	-0.27	0.65	0.60	Moderately Stable	11.42 $\pm$ 0.42
Line 2	0.42	-0.52	0.68	Moderately Stable	11.18 $\pm$ 0.38
Giza 96	-0.35	0.78	0.74	Moderately Stable	10.87 $\pm$ 0.44
Line 3	0.98	1.22	2.18	Unstable	9.76 $\pm$ 0.52

3.3. Mega-Environment Delineation and Genotype Evaluation via GGE Biplot

The GGE biplot analysis effectively captured the patterns of genotype performance and interaction, explaining 79.1% of the total G + GEI variation (Principal Component 1, PC1 = 51.0%; PC2 = 28.1%).

Mega-Environment Identification

The "which-won-where" polygon view of the biplot (Fig. 1) clearly delineated the six test environments into three distinct mega-environments (MEs) based on the winning vertex genotype in each sector

- **ME1 (Favorable):** Encompassed the two Kafr El-Sheikh environments (E1, E2).
- **ME2 (Moderate Stress):** Encompassed the two Damietta environments (E3, E4).
- **ME3 (High Stress):** Encompassed the two El-Sharkia environments (E5, E6).

Environments are represented by red markers (E1-E6); genotypes are represented by blue markers. The polygon connects the vertex genotypes, defining the sectors for the three mega-environments.

Genotype Performance and Stability

The Average Environment Coordination (AEC) view (Fig. 2) was used to simultaneously evaluate genotypes for their mean yield (projection onto the Average Environment Axis, AEA) and stability (deviation from this axis). Genotypes located closer to the AEA (indicated by the single-arrow line) have higher mean yield, while those with shorter projections onto the perpendicular stability line (double-arrow line) are more stable.

Ideal Genotype Ranking

To synthesize both yield and stability, an ideal genotype ranking biplot was constructed (Fig. 3). A theoretical ideal genotype, defined by the highest mean yield and absolute stability, is placed at the center of the concentric circles. The proximity of a genotype to this center indicates its overall desirability.

The ideal genotype is positioned at the center. Genotypes closer to the center are considered more desirable.

Relationships among Environments and Genotypes

The relationships among the six test environments are visualized in Fig. 4. Environments connected by vectors with small angles are positively correlated. Figure 5 illustrates the interrelationships among the seven cotton genotypes.

4. Discussion

The substantial contribution of genotype-by-environment interaction to total yield variation (47.12%) constitutes the pivotal finding of this investigation. This magnitude exceeds environmental main effects and substantially outweighs genotypic differences, confirming that relative cultivar performance in the Nile Delta is inherently context-dependent. A genotype delivering exceptional yields under favorable conditions may perform only moderately—or even poorly—when confronted with environmental constraints. This reality renders pursuit of a single universally adapted cultivar for the entire Delta region biologically unrealistic and agronomically inefficient (Annicchiarico, 2002). Instead, these findings strongly support adoption of spatially explicit cultivar deployment strategies that acknowledge and leverage environmental heterogeneity.

The delineation of three distinct mega-environments through GGE biplot analysis provides an actionable framework for implementing such strategies. The clustering of locations into separate adaptation zones aligns logically with known environmental gradients across the Delta. Kafr El-Sheikh environments formed a high-potential mega-environment where Line 1 not only achieved the highest mean yield but also demonstrated remarkable stability ($ASV = 0.30$). This combination of high productivity and reliability offers particular value to farmers seeking consistent returns under favorable conditions. In the moderate-stress mega-environment represented by Damietta, Line 4—the most stable genotype overall—emerged as the optimal choice. Its performance pattern suggests that stability mechanisms may confer greater advantage than maximum yield potential in environments experiencing moderate but variable stress levels, reflecting the concept of biological buffering where certain genotypes maintain relatively consistent performance across fluctuating conditions (Gauch, 2006). For the high-stress mega-environment (El-Sharkia), the established cultivar Giza 94 demonstrated superior adaptation, validating historical breeding emphasis on resilience traits in commercial varieties. This outcome suggests that cultivar selection for marginal environments should prioritize specific adaptive mechanisms—potentially including root architecture modifications or physiological stress tolerance—over absolute yield potential under ideal conditions.

Methodologically, the complementary application of AMMI and GGE biplot proved particularly valuable. AMMI provided rigorous quantitative stability metrics that objectively ranked genotypes, while GGE biplot translated these statistical insights into intuitive visual representations facilitating practical interpretation. The strong concordance between methods in identifying Lines 1 and 4 as superior performers enhances confidence in these selections. Critically, the integrated approach prevented potential misinterpretation that might arise from considering yield potential alone; genotypes exhibiting high mean performance but substantial instability would have been inappropriately recommended without stability assessment.

These findings carry several practical implications for Egyptian cotton improvement programs. First, breeding networks should establish testing protocols that evaluate advanced lines across representative sites from each mega-environment early in selection cycles. Such spatially distributed testing enables identification of both broadly adapted genotypes and those with specific adaptation to particular zones. Second, crossing strategies could deliberately combine parents with complementary adaptation patterns—for instance, pairing Line 1 (high yield potential in favorable environments) with Giza 94 (stress resilience)—to generate segregating populations potentially exhibiting transgressive segregation for both yield potential and stability. Third, seed distribution systems should adopt zone-specific recommendations rather than uniform cultivar deployment, thereby enhancing farmer profitability through better genotype-environment matching.

This investigation possesses limitations warranting acknowledgment. The two-year evaluation period, while capturing seasonal variation, would benefit from extension across additional growing seasons to strengthen mega-environment definitions and account for inter-annual climatic fluctuations. Furthermore, future research should investigate physiological mechanisms underpinning the stability of Lines 1 and 4—potentially examining root system architecture, stomatal regulation under water deficit, or membrane thermostability—to develop trait-based selection criteria complementing empirical yield evaluation.

5. Conclusions

This study quantified the dominant role of genotype-by-environment interaction in shaping cotton yield variation across the Nile Delta and successfully delineated three distinct mega-environments corresponding to favorable, moderate-stress, and high-stress production zones. The integrated application of AMMI and GGE biplot methodologies proved highly effective for identifying stable high-performing genotypes and mapping their zones of optimal adaptation. Line 1 demonstrated superior performance in favorable environments (Kafr El-Sheikh), Line 4 excelled under moderate stress conditions (Damietta), and Giza 94 maintained reliable yields in high-stress environments (El-Sharkia). We recommend adoption of these spatially targeted cultivar deployment strategies by Egyptian extension services and seed companies. Furthermore, breeding programs should institutionalize mega-environment-based testing protocols to accelerate development of genotypes with defined adaptation patterns. Implementation of these evidence-based recommendations should enhance yield stability,

reduce production risk for farmers, and contribute to sustained productivity across Egypt's cotton-growing regions.

Declarations

Institutional Review Board Statement

Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest:

The authors declare no conflict of interest.

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Author Contribution

F.E.E. and B.A.M. conceptualized the research objectives and designed the field experiments; M.W.E. coordinated field trial implementation across the three locations and supervised data collection; U.A.A. performed the statistical analyses using AMMI and GGE biplot methodologies, prepared all figures and tables, and led manuscript drafting; F.E.E. and U.A.A. jointly interpreted the results and developed cultivar deployment recommendations; B.A.M. and M.W.E. contributed to methodological refinement and validation of environmental characterizations; U.A.A. prepared the original draft of the manuscript; all authors (F.E.E., B.A.M., M.W.E., and U.A.A.) critically reviewed, edited, and approved the final version of the manuscript.

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Data Availability

The raw data supporting the conclusions of this article will be made available by the corresponding author upon reasonable request.

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Figures

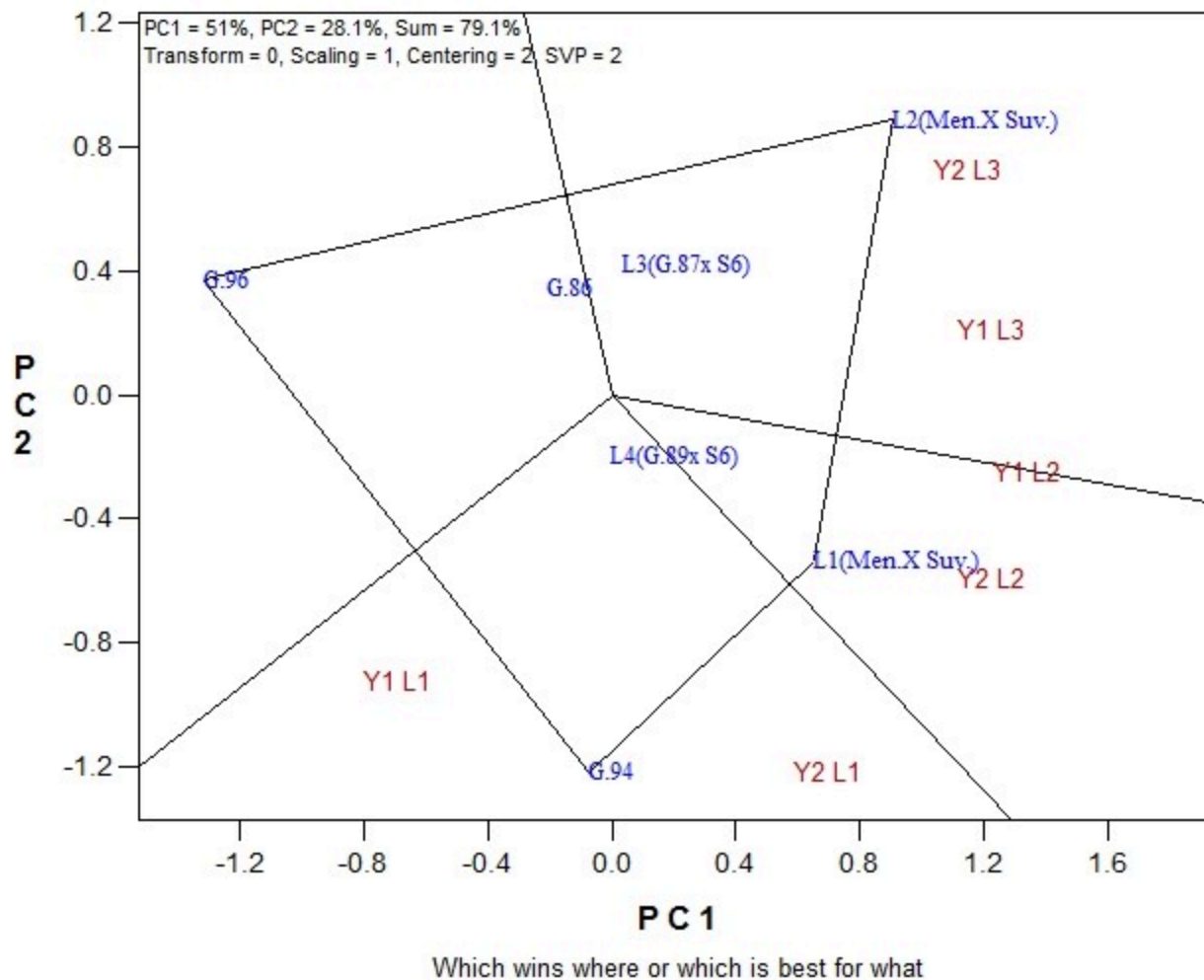


Figure 1

The 'which-won-where' polygon view of the GGE biplot.

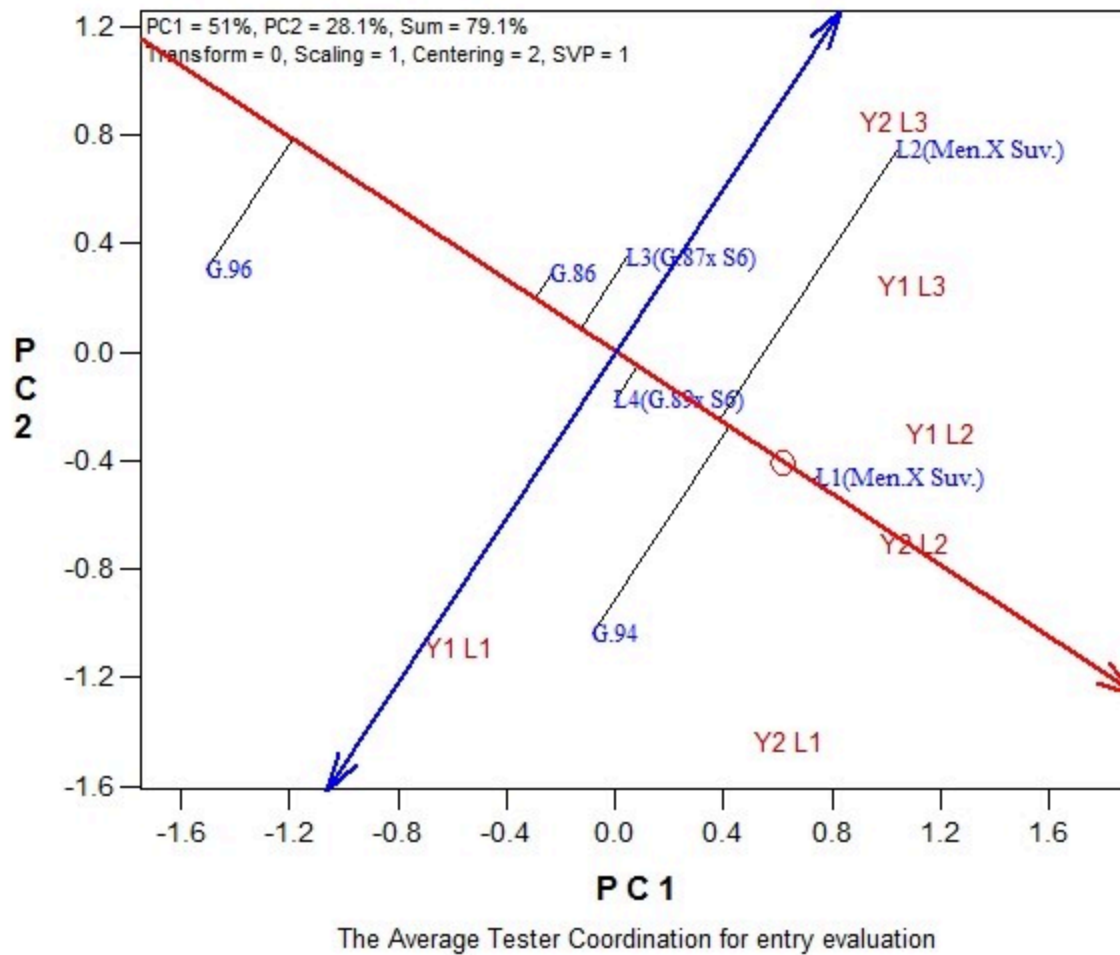


Figure 2

GGE biplot (Average Environment Coordination view) displaying mean performance and stability of the seven genotypes.

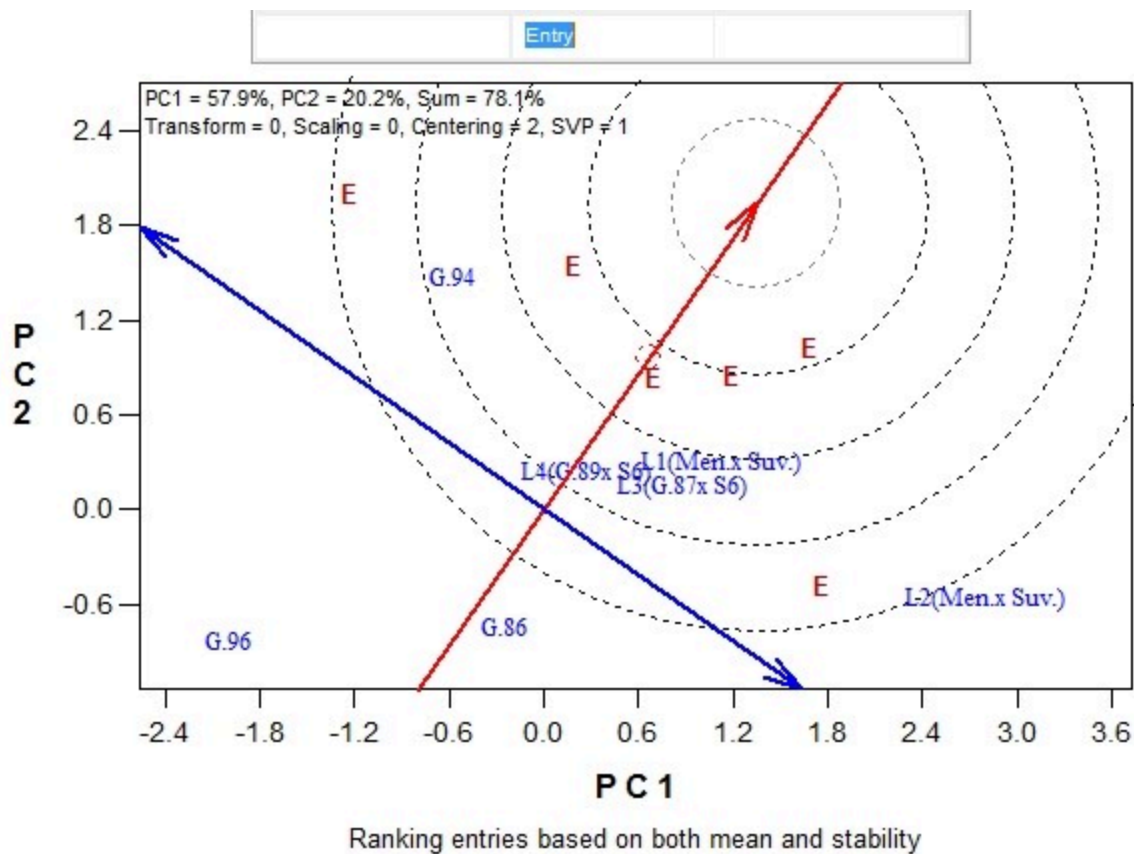


Figure 3

Ranking of genotypes based on their distance from an ideal genotype.

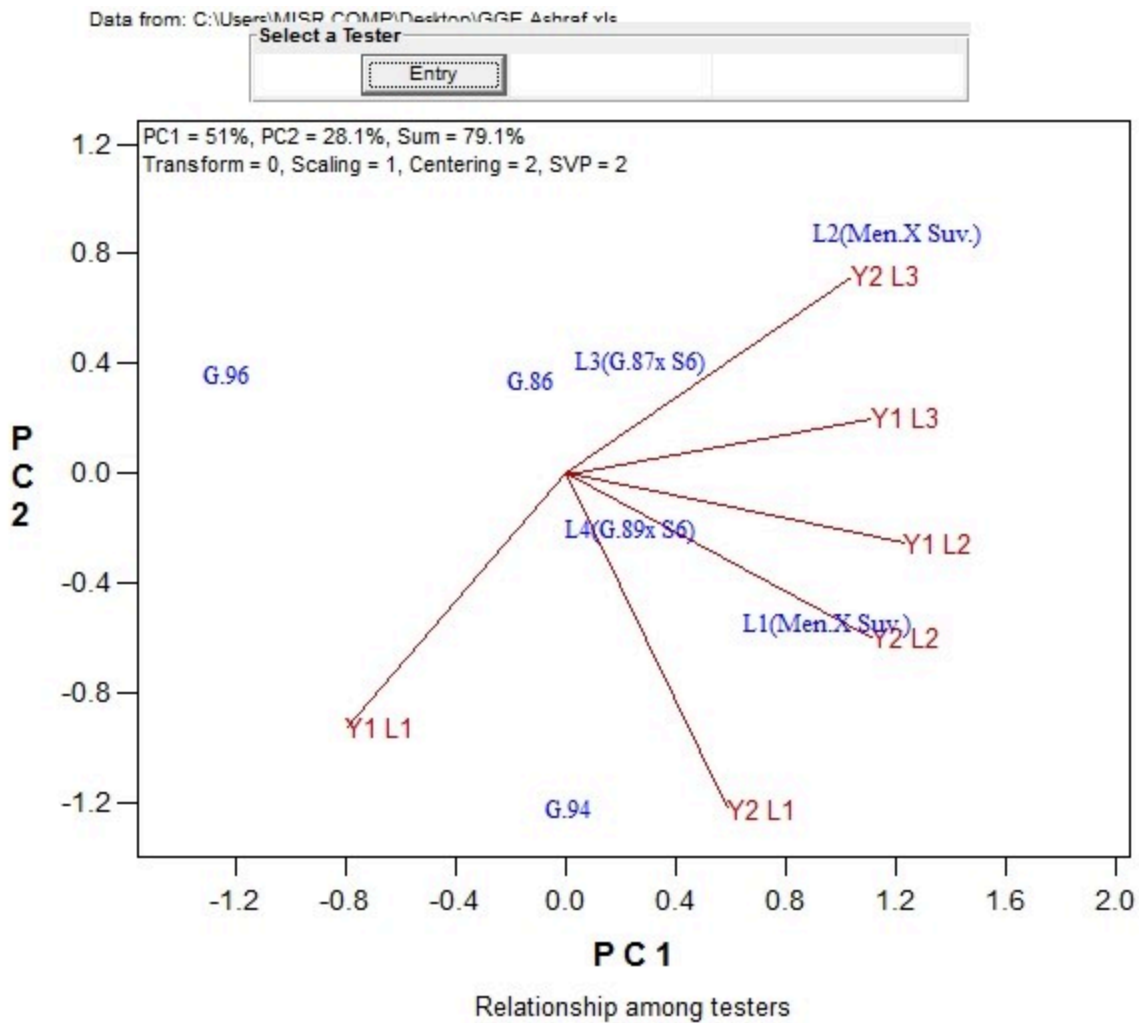


Figure 4

GGE biplot showing the relationships among the six test environments.

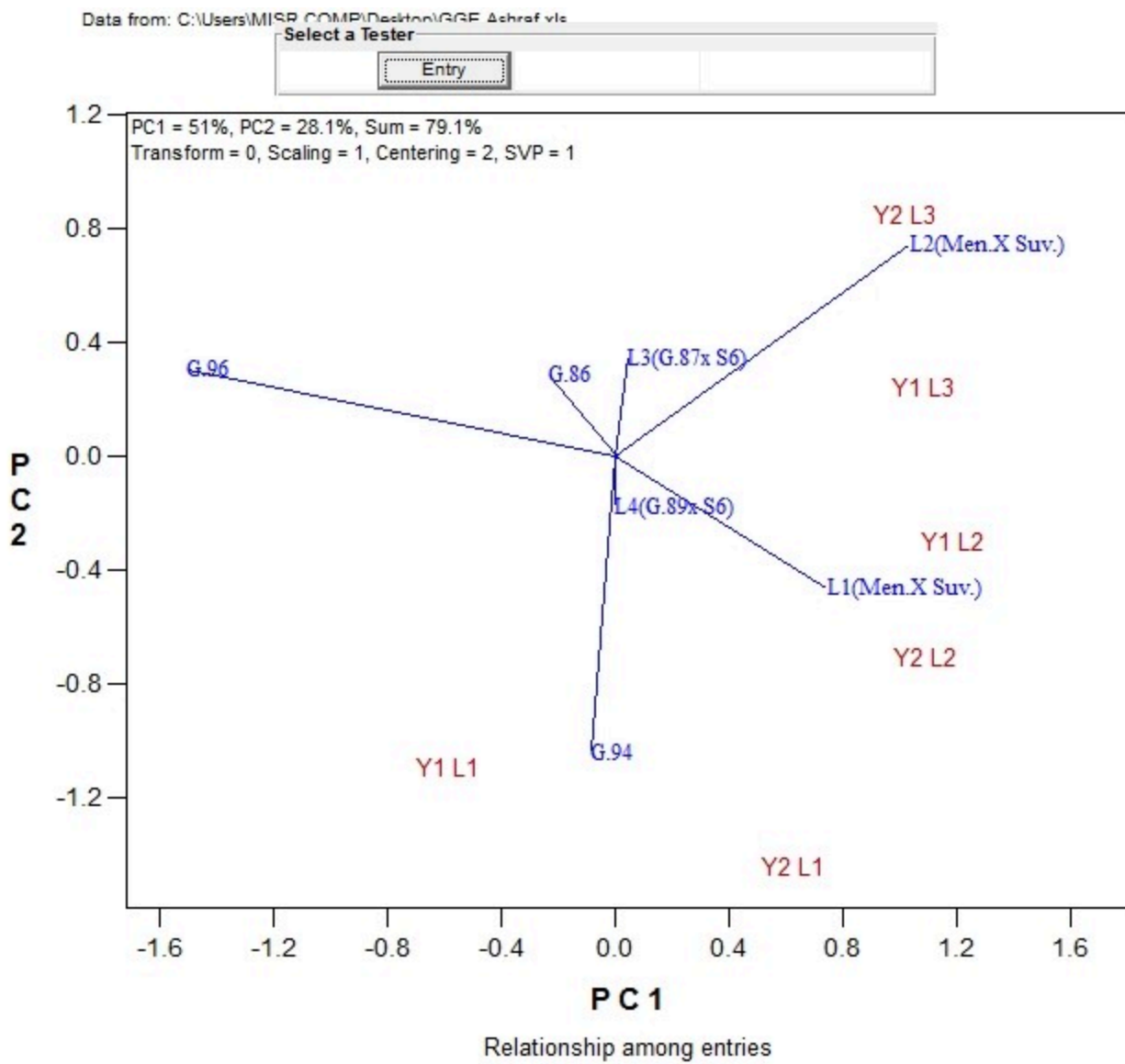


Figure 5

GGE biplot showing the relationships among the seven cotton genotypes.