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A Review of Parametric and AMMI Models for Genotype x Environment (G x E) Interaction in Mulberry

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Mulberry (*Morus* spp.) is a key perennial crop cultivated primarily for its leaves, which serve as the sole food for silkworms. The productivity of mulberry varies widely across different agro-climatic environments due to Genotype x Environment (G x E) interactions, posing a challenge for stable varietal development. In the present review, an attempt has been made to find out the parametric models for the stability of mulberry genotypes across seasons. The importance of G x E interaction and the use of various stability models such as Finlay & Wilkinson, Eberhart & Russell, Perkins & Jinks, Freeman & Perkins and AMMI models in evaluating mulberry genotypes. These models help identify high-yielding and stable genotypes adaptable to diverse environments, improving selection efficiency. Understanding adaptability and stability is crucial for breeding programs aimed at enhancing leaf yield, quality and stress tolerance. The integration of statistical models and multi-

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environment trials facilitates the development of mulberry varieties suited for large-scale sericulture under varying climatic conditions. The study approach ultimately supports sustainable mulberry cultivation and silkworm rearing.

Keywords: Stability analysis; analysis models; mulberry; genotype x environment interaction.

1. INTRODUCTION

Mulberry is cultivated in different parts of the world, and it is an evergreen perennial plant with luxuriant foliage, ultimately used for feeding silkworms (*Bombyx mori* L.). Depending on the location, it is also appreciated for its delicious fruits, medicinal properties, animal feed and landscaping (Bhavyashree & Krishnamurthy, 2015). The crop improvement programmes are mainly based on increasing the quality and quantity of leaves because entire activities and success completely depend on the nutritive value and yield of the mulberry leaves (Hatamzadeh et al., 2011).

The ultimate goal of mulberry breeding is to develop high-productive varieties/hybrids with superior leaf quality at shorter time and reasonable cost. "Mulberry leaf productivity is one of the principal factors that decides the sustainability and profitability of sericulture" (Ashiru, 2002 and Doss et al*.,* 2012). "Mulberry varieties show wide fluctuation in their yield ability when grown over varied agro-climatic conditions. There is a persistent demand for identifying suitable genotypes which can withstand environmental variations and ensure reasonably good yields (Chakravorty et al., 2005). Yield, being a crucial quantitative character, is influenced by various genotypes and environmental factors. Testing breeding lines or advanced generation progenies under different conditions forms an integral part of the breeding programme aimed at identifying stable genotypes which can perform well under different growing situations. Identifying a phenotypically stable variety is particularly important from the point of view of increasing mulberry production.

"Principal Component Analysis (PCA) is a widely used exploratory technique that transforms a set of correlated variables into a smaller number of uncorrelated variables known as principal components" (Muniraja et al., 2011). It facilitates the visualization of relationships among genotypes and traits through a 2D scatter plot, where the geometrical distances help identify correlated traits and genetically similar genotypes (Mohammadi, 2003). "PCA is a powerful method for dimensionality reduction, condensing a large set of variables into a smaller set that retains most of the original information" (Massey, 1965; Jolliffe, 1986). One key application of PCA is in the construction of selection indices by assigning weights to components, enabling the simultaneous improvement of multiple traits, including leaf yield.

"Identifying phenotypically stable varieties is crucial for enhancing mulberry production. Such information is essential for developing effective selection strategies and recognizing genotypes with superior stability across different environments" (Gauch and Zobel, 1996; Kang, 1998). The Additive Main Effects and Multiplicative Interaction (AMMI) analysis is widely employed to investigate genotype × environment interactions (GEI), as it effectively separates main effects from interaction effects, thereby aiding in the assessment of genotype stability to support breeding programs (Crossa et al., 1990; Gauch and Zobel, 1997). "AMMI integrates ANOVA for evaluating genotype and environment main effects with principal component analysis (PCA) for analyzing GEI" (Gauch and Zobel, 1996). However, the AMMI model alone does not provide a quantitative measure of stability. To address this, the AMMI Stability Value (ASV), proposed by Purchase (1997), offers a method to quantify and rank genotypes based on yield stability. ASV is calculated as the distance from zero in a two-dimensional scatter plot of the first and second Interaction Principal Component Axes (IPCA1 and IPCA2). The objective of this study was to identify high-yielding genotypes with superior stability across seasons under rainfed conditions.

Models for estimating G×E interaction have been proposed by several workers. The models of Finlay and Wilkinson (1963); Eberhart and Russel (1966); Perkins and Jinks (1968); and Freeman and Perkins (1971), have been used extensively in different plants for estimation of stability. The present study was undertaken to analyse the stability of yield in some promising mulberry varieties to select a stable one for commercial exploitation in diverse environments the most.

Genotype × Environment (G × E) interaction is a critical factor in plant breeding programs, as it helps in identifying stable genotypes with broad adaptability to varying environmental conditions. When a genotype exhibits differing performance across environments, it indicates the presence of G × E interaction. These differential responses are a clear manifestation of this interaction and present a significant challenge for plant breeders. G × E interaction can influence genetic gains, complicate cultivar recommendations, and impact the selection of genotypes with wide adaptability (Lal et al., 2019; Ahalya et al., 2020).

Stability in mulberry over a wide range of environments is one of the most important parameters to be considered for selecting mulberry cultivars for large-scale cultivation. The leaf yield of mulberry fluctuates with the seasons due to the sensitivity of the genotypes in different growing conditions. G x E interaction exists where the relative performance of varieties changes from one environment to another (Sarkar et al*.,* 2001, Sushmitha et al., 2024). Sarkar et al. (1986) and Bari et al*.* (1990). have emphasised that "a knowledge of the nature and relative magnitude of the genotype-environment interaction has great importance for selecting superior genotypes to be used commercially in diverse environmental conditions. Stable materials are therefore required to obtain the least variability in leaf production per unit area over different locations".

There are parametric as well as nonparametric stability measures available for the adaptability of genotypes. Adugna and Labuschagne (2003), Mohammadi and Amri (2008), Kadhem et al*.* (2010), Pourdad (2010) and Kilic, (2012) have attempted to compare parametric and non-parametric measures for stability, whereas Nagaraja et al*.* (2012, 2013) have studied different parametric stability models. In the present study, an attempt has been made to find out the parametric models for the stability of mulberry genotypes across seasons.

- **Genotype:** It is the genetic makeup of an organism, used to refer to the alleles or variant forms of genes.
- **Environment:** The complex of physical, chemical, and biotic factors that act upon an organism or an ecological community and ultimately determine its form and survival.

1.1 Types of Environments

1) **Micro Environment:** It is a very small, specific area in a habitat, distinguished from its immediate surroundings by factors such as the amount of incident light, the degree of moisture, and the range of temperatures.
2) **Macro Environment:** The environment associated with variables having large and easily recognisable effects is termed as macro-environment and may include differences over years, locations (latitude/altitude) fertiliser levers, planting dates, irrigation schedules, *etc*.

Table 1. Classification of environmental variation

Sl. No.	Predictable variation	Unpredictable variation
1.	It includes all the permanent attributes, features of the environment	It includes fluctuating attributes, features of the environment
2.	Climate, edaphic factors (soil types), day length (photo period), agronomic practices such as planting dates, water management, fertilisation plant density *etc*.	Mild or violent, in weather/season / year with respect to annual precipitation (rainfall), temperature, relative humidity, *etc*.

2. GENOTYPE X ENVIRONMENT INTERACTION

Phenotype is the result of the interplay of a genotype and its environment.

A specified genotype does not exhibit the same phenotypic characteristics under all environments. This variation arising from the lack of correspondence between the genetic and non-genetic effects is known as the Genotype x Environment interaction. However, the influence of seasonal fluctuations as well as differences in the environment due to locations results in genotype interaction. Knowledge of the magnitude and nature of the prevalent genetic variation is necessary for recognising the genetic potential of a particular population. The varieties exhibiting a low G x E interaction will be more stable, while those exhibiting high G x E interaction will be unstable when grown over a variable environment. G x E Interaction results from changes in the magnitude of the differences between genotypes in different environments.

There are two types of G x E Interaction present:

i) **Non-cross-over G × E Interaction:** In which the ranking of genotypes remains constant across environments, and the interaction is significant because of changes in the magnitude of the response
ii) **Crossover G × E Interaction:** In which significant changes in rank occur from one environment to another, where one genotype may be chosen for one environment and other genotype for the other.

2.1 Adaptation

It refers to those changes in the structure or function of an individual/population which lead to better survival in a given environment is known as adaptation.

Main Features: Adaptation favours those characters which are advantageous for survival and through which an individual acquires adaptive value or fitness.

In the process of adaptation, survival is the main concern.

Natural selection plays an important role in the process of adaptation.

2.2 Adaptability

It refers to a genotype's ability to express a relatively consistent phenotype across diverse environmental conditions. This stability results from genetic homeostasis, which is the inherent buffering capacity of a genotype to withstand environmental fluctuations.

2.3 Stability

It refers to a genotype's performance in response to changing environmental conditions over time at a specific location. A stable variety demonstrates minimal sensitivity to temporal environmental fluctuations.

Two Different Concepts of Stability:

1. **The static concept of stability:** A stable genotype possesses an unchanged performance regardless of any variation in the environmental conditions. This stable genotype shows no deviation from the expected character level, which means its variance among environments is zero.
2. **The dynamic concept of stability (LEON 1985):** It is not required that the genotypic response to environmental conditions should be equal for all genotypes.

Stability Analysis: Selection for stability is not feasible without an appropriate biometrical model that provides reliable parameters to rank varieties or breeds based on their stability. A low magnitude of G × E interaction indicates consistent performance of a genotype across diverse environmental conditions.

It consists of the following steps:

- ✓ Location / environment-wise analysis a variance
- ✓ Pooled analysis of variance for all the locations/ environments

Table 2. Comparison of different types of adaptation

Term	Focus Level	Scope of Adaptation	Environment Range
Specific Genotypic Adaptation	Individual genotype	Narrow/specific advantage	Specific conditions
General Genotypic Adaptation	Individual genotype	Broad/general advantage	Multiple conditions
Specific Population Adaptation	Population	Localized adaptation	Particular habitat
General Population Adaptation	Population	Widespread adaptation	Broad range of habitats

If G **×** E interaction is found significant, stability analysis can be carried out by four methods:

1) Finlay and Wilkinson's model (1963)
2) Eberhart and Russell's model (1966)
3) Perkins and Jinks' model (1968)
4) Freeman and Perkins' model (1971)

3. FINLAY AND WILKINSON MODEL

Objective: To evaluate genotypic response across environments using linear regression.

Key Features: Simple linear regression of genotype performance over an environmental index (usually mean performance across all genotypes in each environment). The slope (regression coefficient "b") represents responsiveness or adaptability. Finlay and Wilkinson (1963).

1) Mean performance over environments
2) Regression performance in different environments

Inference:

- The regression coefficient of unity indicates average stability (=1)
- If the regression coefficient is >1, it means below-average stability
- If the regression coefficient is <1, it means above-average stability
- A regression coefficient of 0 would express absolute stability

Application in Mulberry:

- Used to screen mulberry genotypes for stability across different agro-climatic zones (e.g., tropical, subtropical, temperate).
- Helps identify stable, high-yielding genotypes suitable for sericulture under variable climatic conditions.

Model Equation:

Yij=μi+biIj+eijY_{ij} = \mu_i + b_i I_j + e_{ij}Yij=μi+biIj+eij

Where:

- YijY_{ij}Yij: Yield (or performance) of the *i*th genotype in the *j*th environment
- μi\mu_iμi: Mean performance of the *i*th genotype across all environments
- bib_ibi: Regression coefficient (slope) for the *i*th genotype
- IjI_jIj: Environmental index for the *j*th environment
- eije_{ij}eij: Error term (residual)

The model is essentially a linear regression of genotype performance on an environmental index.

4. EBERHART AND RUSSELL MODEL

In 1966, both made further improvements in stability analysis by partitioning the G x E interaction of each variety into two parts, one is the slope of the regression line second is the deviation from the regression line (Eberhart and Russel 1966).

Objective: To enhance Finlay and Wilkinson's model by incorporating a stability parameter (deviation from regression).

In this model, total variance is first divided into two components:

Genotypes × Environment plus interaction (E+G×E)

The second component is further divided into three components:

1) Environment linear
2) G × E linear
3) Pooled deviations

Main features of this model:

This model consists of three parameters:

1) Mean yield over locations
2) Regression coefficient = bi
3) Deviation from regression = s^2di

Application in Mulberry:

- Widely applied in multi-location trials for mulberry germplasm.
- Helps identify genotypes that are both high-yielding and stable in leaf yield, growth traits, and quality under changing environmental conditions.
- Commonly used in breeding programs to develop mulberry varieties adaptable to climate change.

Merits:

- ✓ Analysis of stability parameters is simpler as compared to other models of stability analysis
- ✓ The degree of freedom for the environment is 1
- ✓ It requires less area, hence less expensive when compared to other models
- ✓ It does not provide an independent estimation for the mean performance and environmental index

Model equation:

Yij=μi+βiIj+δijY_{ij} = \mu_i + \beta_i I_j + \delta_{ij}Yij=μi+βiIj+δij

Where:

YijY_{ij}Yij: Mean of the *i*th genotype in the *j*th environment
μi\mu_iμi: Genotypic mean across environments
βi\beta_iβi: Regression coefficient for the *i*th genotype (measures response to environmental changes)
IjI_jIj: Environmental index (deviation of environment mean from grand mean)
δij\delta_{ij}δij: Deviation from regression (captures non-linearity)

Stability Parameters:

Mean performance (μi\mu_iμi)
Regression coefficient (βi\beta_iβi) → Ideal = 1 (linear response)
Deviation from regression (Sdi2S^2_{di}Sdi2) → Ideal = 0 (predictability)
Ideal stable genotype: High μi\mu_iμi, βi≈1\beta_i \approx 1βi≈1, Sdi2≈0S^2_{di} \approx 0Sdi2≈0

5. PERKINS AND JINKS MODEL

Objective: To partition the G × E interaction into predictable and unpredictable components using genotypic regression. Perkins and Jinks (1968).

In this model total variance is first divided into three components.

1. Genotypes
2. Environments
3. Genotypes x Environment

Key Features:

- Similar to Eberhart and Russell, but uses genotype × environment interaction as an index.
    - Linear component (predictable)
    - Non-linear component (unpredictable)
- Employs ANOVA for interaction partitioning.

G × E variance is subdivided into:

a. Heterogeneity due to regression
b. Sum of squares due to remainder

- This model is less expensive than Freeman and Perkins
- It requires less area for experimentation
- The degree of freedom for the environment is e-2
- Analysis is more difficult than the Eberhart and Russell model
- It does not provide an independent estimation of the mean performance and nvironmental index

Application in Mulberry:

- Used in quantitative genetic analysis for traits like leaf yield, biomass, and morphological characters.
- Helps breeders understand which part of the GEI is heritable and manageable in mulberry improvement.

Model equation:

Yij=m+di+ej(1+βi)δij+eijY_{ij} = m + d_i + e_j(1 + \beta_i)\delta_{ij} + e_{ij}Yij=m+di+ej (1+βi)δij+eij

Where:

- mmm: Overall mean
- did_idi: Additive genetic effect of genotype *i*
- eje_jej: Additive environmental effect
- βi\beta_iβi: Regression coefficient of genotype *i*
- δij\delta_{ij}δij: Deviation of genotype *i* in environment *j* from regression
- eije_{ij}eij: Experimental error

This model emphasizes the interaction between genotype and environmental deviations by scaling it with both eje_jej and βi\beta_iβi.

6. FREEMAN AND PERKINS MODEL

Objective: To refine GEI analysis by modifying the experimental design: environment as random and genotype as fixed. Freeman and Perkins (1971).

Key Features:

- Uses split-plot design to test GEI more effectively.
- Focuses on practical plant breeding trials.
- Emphasises the reliability of genotype performance across locations and seasons.

1. Genotypes
2. Environment
3. G × E

The environmental sum of squares is subdivided into two components:

a) Combined regression
b) Residual 1

The interaction variance is also subdivided into two parts:

a) Homogeneity of regression
b) Residual 2

This model also includes three parameters like:

1. Eberhart and Russell model provides independent estimation of mean performance and environmental index.
2. The degree of freedom for environment is e-2, like Perkins and Jinks model.
3. Analysis of this model is more difficult and expensive as compared to earlier two models.

Application in Mulberry:

- Useful in multi-year and multi-site evaluation of mulberry hybrids and cultivars.
- Helps ensure that selected genotypes maintain performance across variable biotic and abiotic stresses.
- Contributes to region-specific recommendations for mulberry cultivation.

Model equation:

Yijk=m+di+ej+gij(1+βi)+eijkY_{ijk} = m + d_i + e_j + g_{ij}(1 + \beta_i) + e_{ijk}Yijk=m+di +ej+gij(1+βi)+eijk

Where:

YijkY_{ijk}Yijk: Observation of genotype *i* in environment *j* and replicate *k*
gijg_{ij}gij: Genotype × environment interaction
βi\beta_iβi: Regression coefficient
eijke_{ijk}eijk: Error term

This model incorporates replicates and more explicitly models the G×E interaction effect, adjusted by genotype responsiveness.

Table 3. Difference between the three models

Model	Focus	Utility in Mulberry Breeding
Finlay & Wilkinson (1963)	Linear response to the environment	Identify genotypes suited to high/low input systems
Eberhart & Russell (1966)	Adaptability + stability	Select stable, high-yielding genotypes for leaf and biomass
Perkins & Jinks (1968)	Partitioning G×E interaction	Quantitative analysis of stability helps understand inheritance
Freeman & Perkins (1971)	Practical multi-site evaluation	Validates genotype performance under real-world field conditions

Table 4. Comparison of three stability models

Sl. No.	Particulars	Eberhart & Russell	Perkins & Jinks	Freeman & Perkins
1.	Parameters used	Three	Three	Three
2.	Fractions of variation	Two-G and E + G × E	Three-G, E and G × E	Three-G, E and G × E
3.	Independent calculation of	Not possible	Not possible	Possible

Sl. No.	Particulars	Eberhart & Russell	Perkins & Jinks	Freeman & Perkins
	mean performance and environmental index			
4.	Degree of freedom for the environment	1	e-2	e-2
5.	Calculation	Simple	Difficult	More difficult
6.	Expenditure involved	Less	Less	More

7. AMMI Model (ADDITIVE MAIN EFFECTS AND MULTIPLICATIVE INTERACTION)

The AMMI (Additive Main effects and Multiplicative Interaction) model combines: Mulberry is a perennial crop cultivated mainly for its leaves, which are the sole food for silkworms. Its productivity varies significantly across different agro-climatic zones, making genotype × environment interaction (GEI) analysis crucial. The AMMI model is widely used in multi-location trials to identify stable and high-performing genotypes of mulberry for leaf yield, quality, and stress tolerance (Crossa et al*.,* 1990).

1. ANOVA (Analysis of Variance) - to capture additive effects of genotype and environment.
2. PCA (Principal Component Analysis) - to analyse multiplicative effects of genotype × environment interaction (GEI).

Key Traits in Mulberry Evaluated Using AMMI:

- Leaf yield (total, per plant, per hectare)
- Biomass productivity
- Shoot and branch growth
- Leaf quality (moisture content, protein, sugar, chlorophyll)
- Stress tolerance (drought, salinity, temperature extremes)

How AMMI model Works in Mulberry Trials:

1. Multi-environment Trials (METs):

- Genotypes are tested across multiple environments (locations or seasons).

2. AMMI Analysis Components:

- **Additive effects**: Environment and genotype main effects
- **Multiplicative effects**: GEI effects analysed through PCA (IPCA scores)

3. Interpretation:

- Mean performance indicates yield potential.
- IPCA scores show stability:
- Near-zero = more stable
- Far from zero = more interactive (responsive but less stable)

The AMMI Model Combines:

- ANOVA (Additive Main Effects) for genotypes and environments
- PCA (Principal Component Analysis) for G×E interaction

AMMI Model Equation:

Yij=μ+Gi+Ej+∑k=1nλkαikγjk+ρijY_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} \lambda_k \alpha_{ik} \gamma_{jk} + \rho_{ij}Yij=μ+Gi+Ej+k=1∑nλkαikγjk+ρij

$$Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} \lambda_k \alpha_{ik} \gamma_{jk} + \rho_{ij}$$

Where:

- YijY_{ij}Yij: Yield (or trait) of the *i-th genotype* in the *j-th environment*
- μ\muμ: Grand mean
- GiG_iGi: Effect of the *i-th genotype*
- EjE_jEj: Effect of the *j-th environment*
- λk\lambda_kλk: Singular value (eigenvalue) of the *k-th* interaction principal component axis (IPCA)
- αik\alpha_{ik}αik: Genotype score for IPCA *k*
- γjk\gamma_{jk}γjk: Environment score for IPCA *k*
- ρij\rho_{ij}ρij: Residual (noise)

Over the seasons, all the sixteen genotypes were highly significant with respect to regression coefficient according to all the three parametric stability models *i.e.,* Eberhart and Russell model, Perkins and Jinks model and Freeman and Perkins model for leaf yield (Table 6) (Bhavya et al*.,* 2017).

Table 5. Advantages in mulberry breeding

Benefit	Description
Better selection	Dissects yield from stability
Visual analysis	AMMI biplots make data intuitive
Adaptability classification	Helps recommend genotypes to specific zones or all zones
Improved recommendation	Useful for national-level varietal release programs

Table 6. Estimation of stability parameters for leaf yield using three different parametric stability models

	Eberhart and Russells			Perkins and Jinks			Freeman and Perkins		
Treatments	**m**	**b_i**	**S^2di**	**m**	**b_i**	**S^2di**	**m**	**b_i**	**S^2di**
ME - 18	2343.35	-2.46	163775.47 **	2064.56	-3.46	163775.47 **	2344.77	-2.34	168807.00 **
ME - 52	1889.14	0.75	224074.17 **	1830.70	-0.25	224074.17 **	1900.13	0.75	218003.30 **
Surat Local	1821.91	4.57	425859.92 **	2108.16	3.57	425859.92 **	1821.85	4.35	458876.00 **
C - 776	2516.65	-1.68	698399.44 **	2474.22	-2.68	698399.44 **	2517.72	-1.60	702722.60 **
Karanahalli	2300.73	2.00 *	17883.74 **	2334.10	1.00*	17883.74 **	2300.01	1.95	16914.13 **
MI - 79	1544.87	1.68	19953.49 **	1592.85	0.68	19953.49 **	1544.87	1.62	20044.98 **
MI -0142	1454.32	0.57	50181.74 **	1480.39	-0.43	50181.74 **	1448.93	0.58	56254.63 **
C - 763	1221.18	0.93	7008.58 **	1247.64	-0.07	7008.58 **	1222.13	0.89	5566.42
M.Indica	2619.79	1.01	801961.85 **	2644.04	0.01	801961.85 **	2611.46	0.74	809109.30 **

** Significant at 5%, ** Significant at 1%*

Table 7. Stable genotypes over years for leaf yield according to different models

Remarks	Eberhartand Russells	Perkins and Jinks	Freeman and Perkins
Well adapted to all environment	-	Karanahalli	-
Poorly adapted to all environments	C-763	C-20	C-763
Specially adapted to favourable environments	ME-18 and MR-2	ME-18 and MR-2	ME-18 and MR-2
Specially adapted to unfavourable environment	Karanahalli and Mi-79	-	Surat local and karanahalli

The adaptability of genotypes across different environments is presented in Table 7. Over the seasons for leaf yield, the genotype Karanahalli was well adapted to all environments. The genotype C-763 was poorly adapted to all environments because it was selected the maximum number of times by different models. "The genotypes ME-18 and MR-18, and MR-2 were specially adapted to a favourable environment because it was selected the maximum number of times by different models. The genotype Karanahalli was also specially adapted to an unfavourable environment because it was selected the maximum number of times by different models. These genotypes can be utilised in breeding programmes to incorporate stability" (Bhavya et al*.,* 2015).

"The ANOVA indicated significant differences (P<0.01) for seasons (E), varieties (G) and G x E interaction for fresh leaf weight and leaf to shoot ratio (Table 8). Leaf yield was significantly affected by the environment and explained 93.2% of the total variation, while G × E interaction and genotype effects captured only 0.5% and 4.4% variation, respectively" (Suresh et al*.,* 2021).

Table 8. AMMI analysis of mulberry genotypes over seasons for leaf yield and its component traits (Suresh et al., 2021)

Source of Variation	d.f.	Fresh leaf weight (g)	Total shoot length(cm)	Leaf to shoot ratio (%)	Leaf yield per plant (g)	%SS
REP(ENV)	3	0.53	31241	12.38	13737	0.80
Genotype(G)	32	6.48**	94518**	37.90**	75605**	4.40
Environment/Season(E)	2	6.68*	5976799**	461.45**	1601497**	93.22
G × E	64	0.62**	41454	20.82**	9301	0.54
IPCA 1	33	0.33	20874	11.91	5410	0.31
IPCA 2	31	0.28	20569	8.81	3841	0.22
Residuals	294	0.31	48356	8.13	8601	0.50

IPCA: Interaction principle component axis; SS: sum of squares
**, ** Significant at 5% & 1% level of significance, respectively*
AMMI analysis: Additive main effects and multiplicative interaction

Table 9. Comparison of mulberry genotypes suitable for rainfed conditions on seasonal performance, AMMI Stability values and annual yield (Suresh et al., 2021)

Genotypes	Seasonal Performance					AMMI Stability				Annual Leaf Yield
	S1	S2	S3	Mean	Rank	IPC1	IPC2	ASV	Rank	kg/yr
PYD 01	719	665	469	618	3	-1.74	0.67	2.25	5	1.852*
PYD 02	552	676	399	542	10	3.98	5.70	7.53	31	1.624
PYD 03	595	550	319	488	17	-2.44	2.18	3.72	19	1.463
PYD 04	670	621	453	581	5	-0.63	-0.33	0.85	3	1.742*
PYD 05	521	510	366	466	21	1.88	-0.89	2.49	9	1.395
PYD 06	561	529	371	487	18	0.45	-0.56	0.79	2	1.459
PYD 07	713	579	433	575	7	-3.90	-2.09	5.25	24	1.725*
PYD 08	770	711	480	654	1	-3.06	1.99	4.27	20	1.960*
PYD 09	619	693	396	569	8	1.05	5.95	6.09	27	1.706*
PYD 10	481	520	331	444	23	2.78	1.35	3.69	18	1.331
PYD 11	608	488	326	474	20	-3.75	-1.34	4.82	22	1.421
PYD 12	640	490	360	497	16	-4.14	-2.92	5.89	25	1.489
PYD 13	394	433	355	394	30	6.24	-3.01	8.28	33	1.181
PYD 14	416	438	360	405	28	5.47	-3.19	7.48	29	1.212
PYD 15	653	576	445	558	9	-0.78	-2.09	2.30	6	1.674*
PYD 16	640	567	376	528	13	-2.45	0.29	3.04	14	1.581
PYD 17	455	461	227	381	31	-0.17	2.80	2.81	11	1.141
PYD 18	391	411	286	362	33	3.88	-1.33	4.98	23	1.086
PYD 19	521	365	249	378	32	-3.96	-3.48	6.01	26	1.133
PYD 20	427	479	383	429	26	6.29	-2.16	8.07	32	1.286

Genotypes	Seasonal Performance					AMMI Stability				Annual Leaf Yield
	S1	S2	S3	Mean	Rank	IPC1	IPC2	ASV	Rank	kg/yr
PYD 21	668	637	478	594	4	0.48	-0.52	0.79	1	1.783*
PYD 22	500	410	291	400	29	-1.00	-2.71	2.98	13	1.198
PYD 23	611	548	435	531	12	0.42	-2.66	2.71	10	1.594
PYD 24	555	571	386	504	15	1.84	1.00	2.48	8	1.510
PYD 25	571	396	254	407	27	-5.68	-2.69	7.52	30	1.220
PYD 26	650	589	496	578	6	1.13	-3.41	3.68	17	1.733*
PYD 27	720	748	437	635	2	-1.54	6.04	6.33	28	1.904*
PYD 28	511	501	345	452	22	1.53	-0.42	1.94	4	1.355
PYD 29	511	472	346	443	24	1.15	-1.88	2.36	7	1.328
PYD 30	565	494	269	443	25	-3.43	1.65	4.55	21	1.327
C-1730	536	558	332	475	19	0.85	2.65	2.85	12	1.423
S-1635	569	590	360	506	14	-1.45	2.62	3.17	15	1.518
C-2038*	626	606	369	534	11	-1.45	2.62	3.17	16	1.600

IPCA: Interaction principal component axis
ASV: AMMI Stability value

The performance of genotypes averaged over three seasons across two years is presented in Table 9. Among the genotypes, PYD 08 recorded the highest leaf yield per plant (654 g), while PYD 18 produced the lowest (362 g). Although the genotypes exhibited some inconsistency across seasons, PYD 08 (654 g), PYD 27 (635 g), and PYD 01 (618 g) emerged as the top performers. In contrast, PYD 18, PYD 19, PYD 17, PYD 13 and PYD 22 showed poor performance, while the remaining genotypes were classified as moderate yielders. The mean leaf yield across genotypes ranged from 770 g in July (S1) to 227 g in November (S3). The overall average yield across all seasons and genotypes was 495 g. Based on the environmental index, July was identified as the most favorable season, September as moderately favorable and November as the least favorable (Suresh et al., 2021).

8. CHALLENGES AND FUTURE DIRECTIONS

Mulberry breeding faces challenges due to complex genotype × environment interactions, causing inconsistent genotype performance across varied climates. The crop's long breeding cycle and environmental unpredictability make it difficult to develop stable varieties quickly. Limited access to advanced phenotyping tools and genetic resources further restricts progress. Future research should integrate molecular breeding techniques, like genomic selection, with traditional stability analysis to speed up improvement. Utilising remote sensing and machine learning can enhance the accuracy of multi-environment trials and G×E modelling. Emphasis on breeding climate-resilient and region-specific mulberry varieties will help address emerging abiotic stresses and local adaptation. Expanding genetic diversity through germplasm exploration remains essential for developing stable, high-yielding mulberry cultivars.

9. CONCLUSION

Genotype × Environment interaction plays a vital role in mulberry breeding by influencing the stability and adaptability of genotypes across diverse agro-climatic conditions. Identifying stable, high-yielding mulberry varieties is essential to ensure consistent leaf production for sericulture. Various stability models like Finlay & Wilkinson, Eberhart & Russell, Perkins & Jinks, Freeman & Perkins and AMMI provide effective tools to analyse and interpret G×E interactions. Each model has unique strengths and applications, helping breeders select genotypes suited for specific or wide-ranging environments. The AMMI model, in particular, offers a comprehensive approach by combining additive and multiplicative effects. Ultimately, understanding G×E interaction and stability enables breeders to develop mulberry cultivars with superior leaf yield and quality that perform reliably under variable environmental conditions. This contributes significantly to the sustainability and productivity of sericulture industries worldwide.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models

(ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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