**Review Article**

**"Genotype × Environment Interaction and Stability Assessment in Mulberry: Comparative Evaluation of Parametric and AMMI Models"**

**Application of Parametric and AMMI Models for Stability and Adaptation Analysis in Mulberry (Morus spp.)"**

**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 × environment (G×E) interactions, posing a challenge for stable varietal development. This study reviews the importance of G×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-environment trials facilitates the development of mulberry varieties suited for large-scale sericulture under varying climatic conditions. This approach ultimately supports sustainable mulberry cultivation and silkworm rearing.

**Keywords:** Stability analysis, Analysis models, mulberry, Genotype x Environment interaction

**Introduction**

Mulberry is cultivated in different parts of the world which 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. The crop improvement programmes mainly based on increasing the quality and quantity of leaf because of entire activities and success completely depend on the nutritive value and yield of the mulberry leaves.

The ultimate goal of mulberry breeding is to develop high productive varities/hybrids with superior leaf quality at less possible time and reasonable cost. Mulberry leaf productivity is one of the principal factors that decide the sustainability and profitability of sericulture (Ashiru, 2002 and Doss *et al.,* 2012). Mulberry varieties show wide fluctuation in their yielding ability when grown over varied agro-climatic conditions. There is persistent demand for identifying suitable genotypes which can withstand environmental variations and ensure reasonably good yields. 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 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 an exploratory tool that transforms a number of correlated variables into a smaller number of uncorrelated variables called principal components (Muniraja *et al.,* 2011). PCA results in generation of a 2D scatter plot of genotypes and component traits, whose geometrical distances helps in identification of correlated traits and genetically similar genotypes (Mohammadi, 2003). PCA is a well-known method of dimension reduction that reduce a large set of variables into a small set, that still contains most of the information in the large set (Massay,1965 and Jolliffie,1986).PCA has many applications and among which computing an index by assigning the weights is one. PCA-based selection index targets the simultaneous improvement of several traits at the same time, including the leaf yield.

Identifying a phenotypically stable variety is very important from the point of increasing mulberry production. This information is required for planning better selection strategies and to identify genotypes with better stability across environments ([Gauch](https://www.frontiersin.org/articles/10.3389/fpls.2016.01530/full" \l "B25) [and Zobel, 1996](https://www.frontiersin.org/articles/10.3389/fpls.2016.01530/full#B25) and [Kang, 1998)](https://www.frontiersin.org/articles/10.3389/fpls.2016.01530/full#B38).Additive main effects and multiplicative interaction (AMMI) analysis is widely used for GEI investigation and it clearly separates main effects and interaction effects, which helps in understanding stability of genotypes to support the breeding programme (Crossa *et al.,* 1990; Gauch and Zobel, 1997). It combines ANOVA for the genotype and environment main effects with principal components analysis of GEI (Gauch and Zobel, 1996). However AMMI model does not make provision for a quantitative stability measure. AMMI stability value (ASV) proposed by Purchase (1997) quantifies and rank genotypes according to their yield stability. ASV is the distance from zero in a two dimensional scatter of IPCA 1 scores against IPCA 2 scores. The aim of this investigation was to identify superior genotypes with better yield stability across seasons for rainfed condition.

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

The Genotype x Environment interaction is an important parameter for plant breeding programme to identify the stable genotypes that are widely adapted to unique environment. It is observed that the relative performance of genotype to give the same response in different environments is a definite indication of genotype x environment (GxE) interaction. These differential responses of genotypes in different environments are termed as GxE-interaction. The occurrence of GxE interaction has been a major challenge for plant breeders. Stability in mulberry over wide range of environment is one of the most important parameters to be considered for selecting mulberry cultivars for large scale cultivation. G x E interaction exists where the relative performance of varieties changes from environment to other environment (Sarkar *et al.,* 2001). Sarkar *et al*.(1986) and Bari *et al.* (1990). have emphasized 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 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), Hossein *et al.* (2011) and Hasan 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 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, biotic factor that act upon an organism or an ecological community and ultimately determine its form and survival.

**Types of Environment**

1. Micro Environment: It is 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 recognizable effect is termed as macro-environmentand may include differences over years, locations (latitude / altitude) fertilizer levers, planting dates, irrigation schedules *etc*.

**Table 1: Classification of environmental variation:**

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

**Genotype x Environment interaction**

Phenotype is the result of 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 × 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 natureof the prevalent genetic variation is necessary for recognizing the genetic potential of a particular population. The varieties exhibiting a low G×E interaction will be more stable while those exhibiting high G×E interaction will be unstablewhen grown over variable environment. G **×** E Interaction results from changes in the magnitude of the differences between genotypes in different environments

There are two types of G **×** 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 occurs from one environment to another where one genotype may be choosen for one environment and other genotype for other

**Adaptation:**

It refers to those changes in 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

**Types of adaptation:**

Specific genotypic adaptation: Specific genotypic adaptation refers to the adaptation of particular genotypes (individual genetic makeups) to specific environmental conditions or stressors. This type of adaptation involves genetic changes that provide an advantage in a narrow or specific environment. It usually results from natural selection acting on genetic variation.

**Example:** A specific genotype in a plant species may allow it to survive in high-salinity soil, but not in normal soil.

General genotypic adaptation: General genotypic adaptation involves genetic traits or genotypes that confer a broad or general advantage across a variety of environments. These adaptations are not limited to a single environmental condition. They tend to be robust, helping the organism survive under a range of situations.

**Example:** A genotype that helps an organism regulate body temperature over a wide range of climates.

Specific population adaptation: Specific population adaptation occurs when a distinct population of a species adapts to a specific local environment or set of environmental conditions. This is often seen in sub-populations that are geographically or ecologically isolated. The adaptation is not necessarily shared across the entire species.

**Example:** A mountain population of goats evolving stronger lungs to cope with high altitudes.

General population adaptation: General population adaptation refers to traits or characteristics that evolve across an entire population or species, providing a broad fitness benefit. This adaptation is usually species-wide or common across a large group. It results from selection pressures that are similar across the species' range.

**Example:** Humans developing sweat glands to cool the body—an adaptation shared broadly across populations

**Table 2: 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 |

**Adaptability:**

It is the ability of a genotype to produce relatively narrow range of phenotypes in different environments. It is the result of genetic homeostasis, refers to the buffering capacity of a genotype to environmental fluctuations.

**Stability:**

It refers to its performance with respective changing environmentalfactors overtime within a given location. This means that a stable variety is less sensitive to the temporal environmental changes that may take place.

**Two different concepts of stability:**

**1. The static concept of stability:** A stable genotypes possesses an unchanged performance regardless of any variation of the environmental conditions. This stable genotype shows no deviation from the expected character level, that means its variance among environment 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 possible until a biometrical model with suitable parametersis available to provide criteria necessary to rank varieties / breeds for stability. Low magnitude of G × E interactioninvolves the consistent performance of a population over variable environments

It consists of following steps:

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

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

1. Finlay and Wilkinson model (1963)
2. Eberhat and Russell model (1966)
3. Perkins and Jinks model (1968)
4. Freeman and Perkins model (1971)
5. **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 environment

**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
* 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​+bi​Ij​+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.

**2. EBERHART AND RUSSELL MODEL:**

In 1966 both made further improvement in stability analysis by partitioning the G×E interaction of each variety into two parts, one is slope of the regression linesecond is deviation from regression line. (Eberhart, S. A. and Russel, W. A. 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 = s²di

**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 simple as compared to other models of stability analysis
* The degree of freedom for environment is 1
* It requires less area hence less expensive when compared to other models
* It does not provide independent estimation for mean performance and environmental index

**Model equation**:

Yij=μi+βiIj+δijY\_{ij} = \mu\_i + \beta\_i I\_j + \delta\_{ij}Yij​=μi​+βi​Ij​+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

1. **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 sub divided into:**

1. Heterogeneity due to regression
2. Sum of square due to remainder

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

1. **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​.

1. **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.
* Emphasizes reliability of genotype performance across locations and seasons.

1) Genotypes

2) Environment

3) G × E

**The environmental sum of squares is sub divided into two components**

1. Combined regression
2. 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 and 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 three models**

|  |  |  |
| --- | --- | --- |
| **Model** | **Focus** | **Utility in Mulberry Breeding** |
| Finlay & Wilkinson (1963) | Linear response to 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 mean performance and environmental index | Not possible | Not possible | Possible |
| 4. | Degree of freedom for environment | 1 | e-2 | e-2 |
| 5. | Calculation | Simple | Difficult | More difficult |
| 6. | Expenditure involved | Less | Less | More |

**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 analyze 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 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 analyzed 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)

**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 |

**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∑n​λk​αik​γjk​+ρij​

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)

**Table 6: Analysis of variance for Genotypic** x **Environment (GE) interaction following   
 Eberhart and Russell (1966)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **d.f.** | **Plant height (cm)** | **Leaf/meter (Nos.)** | **Leaf area (cm2)** | **Single leaf weight (g)** | **Leaf yield (g)** | **Consumable leaf weight (g)** |
| **Varieties** | 12 | 1900.74\*\* | 149.60\*\* | 11503.38\*\* | 8.41\*\* | 74791.04\*\* | 51784.93\*\* |
| **Environment+(Variety xEnvironment)** | 91 | 21427.77\*\* | 10.55\*\* | 1210.15\*\* | 0.31\*\* | 12627.60\*\* | 11861.54\*\* |
| **Environment (Linear)** | 1 | 138649.81\*\* | 114.27\*\* | 49967.40\*\* | 7.59\*\* | 627934.79\*\* | 539799.15\*\* |
| **Varietyx Environment (Linear)** | 12 | 492.59\*\* | 14.21\*\* | 1252.25\*\* | 0.43\*\* | 4636.24\*\* | 8352.20\*\* |
| **Pooled deviation** | 78 | 645.56\*\* | 8.66\*\* | 578.57\*\* | 0.20\*\* | 5968.49\*\* | 5633.01\*\* |
| **Pooled Error** | **194** | **50.27** | **0.566** | **99.747** | **0.030** | **620.60** | **436.213** |

The varieties significantly interacted with additive environments for all the growth characters and leaf yield (Table 6). This was evident from the significant environment (varieties × environments) mean squares. This G x E interaction was due to the both linear and non-linear components. However, the linear component was more pronounced for leaf/m, leaf area and single leaf weight. For rest of the characters both the linear and nonlinear components were almost equally important. (Chakravorty *et al.,* 2005)

**Table 7: Estimation of stability parameters for leaf yield using three different   
 parametric stability models**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Eberhart and Russells** | | | | **Perkins and Jinks** | | | **Freeman and Perkins** | | |
| **Treatments** | **m** | **bi** | **S2di** | **m** | **bi** | **S2di** | **m** | **bi** | S2di |
| **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%

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 7). (Bhavya *et al.,* 2015)

**Table 8: 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 aadaptability of genotypes across different environments is presented in (Table 8). 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 maximum number of time by different models. The genotypes ME-18 and MR-18 and MR-2 were specially adapted to favourable environment because it was selected maximum number of time by different models. The genotype Karanahalli was also specially adapted to unfavourable environment because it was selected maximum number of time by different models. These genotypes can be utilized in breeding programmes to incorporate stability. (Bhavya *et al.,* 2015)

**Table 9: AMMI analysis of mulberry genotypes over   
 seasons for leaf yield and its component traits**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **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

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 9). 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 10: Comparison of mulberry genotypes suitable for rainfed conditions on   
 seasonal performance, AMMI Stability values and annual yield**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **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 |
| **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 principle component axis

ASV: AMMI Stability value

The performance of genotypes averaged over three seasons for two years is presented in (Table 10) which depict that PYD 08 and PYD 18 had the highest (654g) and the lowest (362g) leaf yield per plant, respectively. Although the genotypes showed less consistent performances across all seasons, PYD 08 (654g), PYD 27 (635g), PYD 01 (618g) were the top performers, while PYD 18, PYD 19, PYD 17, PYD 13, PYD 22 were the poorest and remaining were moderate yielders. The mean leaf yield of all the genotypes ranged from 770g in July (S1) to 227g in Nov season (S3). The average productivity of all seasons for all the genotypes was 495g. On the basis of environmental index value considering negative and positive, Nov season was found to be poor, September was medium and July was the most favorable environment. (Suresh *et al.,* 2021)

**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. Utilizing remote sensing and machine learning can enhance the accuracy of multi-environment trials and G×E modeling. 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.

**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 analyze 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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