GMR
The Original

STABILITY OF CHILLI (*CAPSICUM ANNUUM* L.) HYBRIDS ACROSS ENVIRONMENTS USING EBERHART-RUSSELL AND AMMI MODELS

Jogdhande Srinivas[1*], K. Ravinder Reddy[2], P. Saidaiah[3], K. Anitha[4] M. Balram[5], Tanmoy Sarkar[6]

[1*,2]Department of Vegetable Science, SKLTGHU, Mulugu, Siddipet District, Telangana, India - 500030.
[3]Department of Genetics and Plant Breeding, SKLTGHU, Mulugu, Siddipet District, Telangana, India - 500030.
[4]Department of Plant Pathology, NBPGR, Rajendranagar, Hyderabad, Telangana, India - 500030.
[5]Department of Genetics and Plant Breeding, PJTAU, Rajendranagar, Hyderabad, Telangana, India - 500030.
[6*]Department of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, India, 700121,
[1*]**Corresponding author:** Jogdhande Srinivas, Email: srinivasjogi2019@gmail.com

ABSTRACT

Genotype x environment (G x E) interaction limits reliable selection of high-yielding chilli hybrids across contrasting production zones. This study evaluated yield stability, environmental responsiveness and field tolerance to anthracnose in 13 parents, 30 F1 hybrids and three commercial checks across Rajendranagar, Warangal and Adilabad, Telangana, India. The material was generated through a Line x Tester mating design and evaluated in randomized block designs with three replications. Stability was assessed using the Eberhart-Russell regression model and the Additive Main Effects and Multiplicative Interaction (AMMI) model. Pooled analysis of variance detected highly significant genotype, environment and G x E effects for major yield traits. Environmental indices classified Rajendranagar as favourable (Ij = +44.26), Warangal as intermediate (Ij = 0.00) and Adilabad as stressful (Ij = -44.26). A highly significant pooled deviation for fresh fruit yield (363.070) indicated an important non-linear interaction component. AMMI analysis partitioned the interaction into IPCA 1 (70.8%) and IPCA 2 (29.2%). Cross 4 (L2 x T1) combined high mean yield (411.70 g plant-1), a regression coefficient near unity (bi = 1.02) and an IPCA 1 score near zero (+0.04), indicating broad stability. Cross 12 (L4 x T3; bi = 1.48) showed adaptation to favourable high-input conditions, whereas Cross 18 (L6 x T3; bi = 0.52) showed adaptation to the stress-prone environment. Natural field screening also identified resistant parental sources to anthracnose. The combined regression-AMMI approach therefore provides breeders with complementary criteria for identifying broadly adapted and environment-specific chilli hybrids for further multi-season and multi-location validation in Telangana.

KEYWORDS: adaptation, AMMI model, anthracnose, Capsicum annuum, Eberhart-Russell model, genotype x environment interaction, Line x Tester, yield stability.

INTRODUCTION

Chilli (*Capsicum annuum* L.) is an indispensable commercial spice-cum-vegetable crop belonging to the family Solanaceae, widely valued for its biting pungency (capsaicin alkaloid) and vibrant red colour (capsanthin pigment). Globally, chilli peppers are an essential commercial commodity spanning over 90 tropical and subtropical nations. According to the recent agricultural baseline figures published by FAOSTAT, 2024), the global land allocation for primary vegetable and spice crops has stabilized at 1.5 billion hectares, yielding approximately 59 million tonnes of fresh and dried chillies annually. Within this global market, India remains the single largest producer, contributing an annual dry output of approximately 1.87 million tonnes. Despite its immense economic significance, the average productivity of chilli remains restricted by biotic constraints most notably anthracnose or fruit rot caused by *Colletotrichum capsici* and abiotic stressors stemming from shifting weather patterns across diverse agro-climatic zones. Chilli stands as a vital commercial spice and vegetable crop in India, heavily subject to environmental fluctuations (Mahapatra and Sahoo, 2018). Despite improvement in chili production technologies over the years, the rise in production is not linear, which can be largely ascribed to the lack of availability of improved cultivar options with high yield and with host resistance to biotic and abiotic stresses (Barchenger et al., 2018; Chhapekar et al., 2018; Nalla et al., 2023; Swaroop et al., 2025). Because anthracnose disease severity is highly dependent on microclimatic variables, thereby acting as a primary component of Genotype x Environment Interactions, this manuscript shifts focus from isolated pathological screening to a comprehensive, multi-environmental yield stability analysis to identify robust hybrids capable of maintaining productivity under varying regional pressures.

A perennial challenge in chilli breeding is the presence of Genotype × Environment (G × E) interactions. Quantitative characters like fruit yield, number of fruits per plant and individual fruit weight are polygenically inherited and strongly influenced by environmental shifts. When genotypes respond differentially to changing agro-climatic factors, the progress of selection is severely compromised. Hence, relying solely on per se performance across a single location can lead to inaccurate recommendations. To mitigate this risk, plant breeders exploit mating frameworks like the Line × Tester design to evaluate specific combining ability (SCA) and general combining ability (GCA) while simultaneously subjecting populations to multi-environment trials. The phenotypic expression of quantitative traits like fresh fruit yield per plant is unstable without partitioning the G × E interactions (Comstock and Moll, 1963; Degefa et al., 2024).

The mathematical formulation developed by Eberhart and Russell (1966) serves as a classic, computationally robust tool to partition the G × E interaction into linear and non-linear components. A stable genotype is traditionally defined as one maintaining a high mean yield, a regression coefficient close to unity (bi = 1.0) and a minimal deviation from regression S2 di = 0). However, when multi-environment trials exhibit large, unpredictable non-linear components (pooled deviations), the classic linear regression model alone is insufficient to capture the underlying multiplicative structures. The Additive Main Effects and Multiplicative Interaction (AMMI) model addresses this limitation by combining standard ANOVA for main effects with Principal Component Analysis (PCA) for the interaction codes.

While previous stability studies in chilli have separately evaluated line performance or local adaptability, there is a critical lack of research combining Line x Tester mating designs with dual linear and multiplicative stability models across distinct agro-climatic zones. Furthermore, multi-environment trials rarely integrate field evaluation for endemic biotic threats like anthracnose directly into yield stability formulations. This study fills this gap by deploying an integrated Eberhart-Russell and AMMI analytical framework on 30 Line x Tester derived F1 hybrids across three contrasting production zones in Telangana. By partitioning interaction variance into linear responsiveness and multiplicative IPCA axes, this work provides a framework for selecting both broadly stable hybrids and niche-specific cultivars tailored for high-input or stress-prone farming systems.

This investigation was undertaken to elucidate the magnitude of G × E interactions, compute location-specific environmental indices and systematically identify high-yielding, anthracnose-tolerant chilli hybrids possessing high stability across the major production environments of Telangana.

MATERIALS AND METHODS

Experimental Sites and Agro-Climatic Profiling

Multi-environment trials were conducted simultaneously during the Rabi season across three distinct agro-climatic zones under Sri Konda Laxman Telangana State Horticultural University (SKLTGHU), Telangana, India.

Environment 1 (E1 - Southern Telangana Zone): College of Horticulture, Rajendranagar, Hyderabad (17°19' N latitude, 78°28' E longitude; elevation 542.6 m above mean sea level (MSL). The soil texture is sandy loam, with a pH of 7.4, an organic carbon content of 0.52% and high fertility under optimised management (High-Input/ Favourable macro-environment).

Environment 2 (E2 - Central Telangana Zone): JVR Horticultural Research Station, Malyal, Warangal (17°58' N latitude, 79°58' E longitude; elevation 264.0 m MSL). The soil is red sandy loam with a pH of 6.8 and organic carbon content of 0.45% (Intermediate / Average macro-environment).

Environment 3 (E3 - Northern Telangana Zone): Horticultural Research Station, Adilabad (19°40' N latitude, 78°23' E longitude; elevation 264.5 m MSL). The soil is deep black clay loam with a pH of 7.9, subject to greater ambient temperature fluctuations and moisture deficits during crop maturity (High-Stress / Marginal macro-environment).

Genetic Materials and Hybrid Generation

The experimental genetic material comprised 46 entries:

13 Parents: 10 diverse maternal lines (L1 to L10 and 3 paternal testers (T1 to T3), selected based on Mahalanobis D2 genetic distance and varying levels of field tolerance to anthracnose.

30 F1 Hybrids: Developed by crossing the 10 lines with 3 testers in a Line × Tester mating design (Kempthorne, 1957) during the Kharif season (Fig 1).

3 Commercial Checks: Standard national/regional hybrid checks-Sindhur, Arka Harita and Arka Meghana.



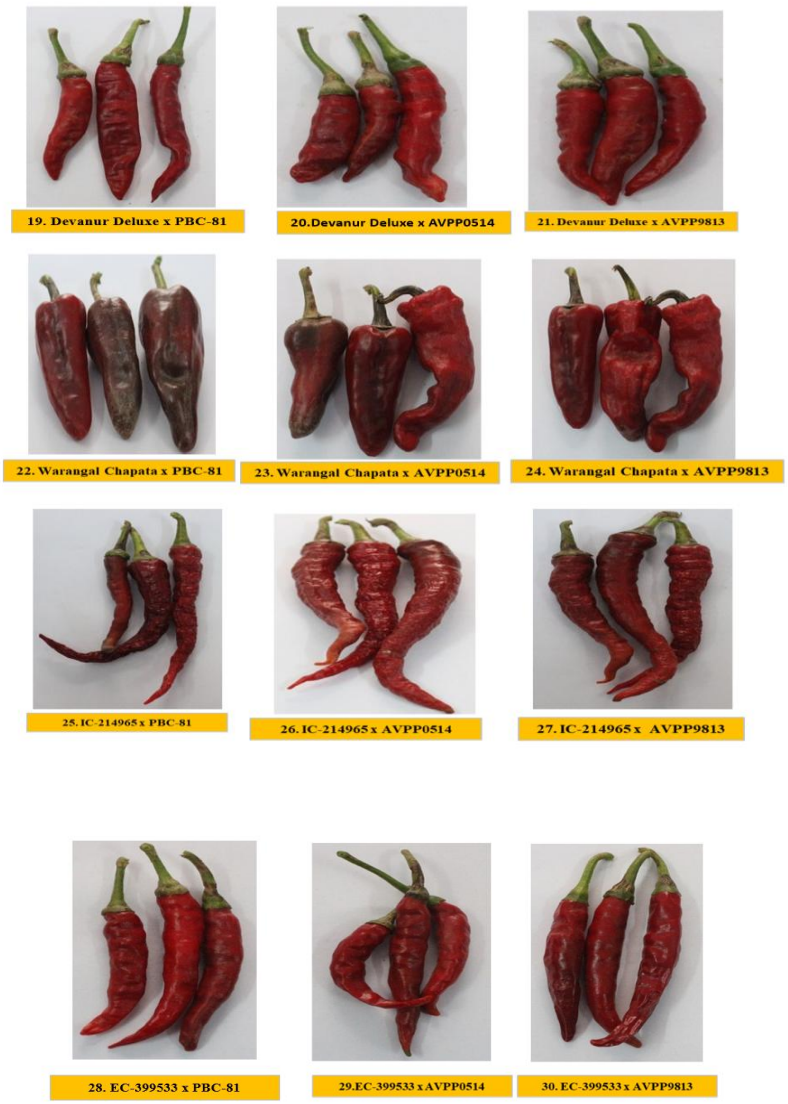


Figure 1: Phenotypic variation in fruit morphology among selected (F1) chilli (*Capsicum annuum* L.) hybrids evaluated for yield stability.

Nursery management, experimental design and field cultivation

Seedlings were raised in 98-cell pro-trays filled with sterilized coco-peat under polyhouse conditions. Nursery care followed standardized prophylactic plant protection measures.

Experimental Design: Randomized Block Design (RBD) with three replications at each testing location.

Plot Configuration: 30-day-old healthy, uniform seedlings were transplanted into double-row beds. Each plot measured 4.5 m x 1.8 m (8.1 m2) with an inter-row and intra-row spacing of 60 x 45 cm, accommodating 30 plants per plot per replication.

Nutrient Management: Recommended Dose of Fertilizers (RDF) of 150 kg N, 60 kg P2O5 and 80 kg K2O ha-1 was applied uniformly. Full doses of P2O5 and K2O along with 1/3rd of Nitrogen were applied as basal dressing during land preparation. The remaining Nitrogen was top-dressed in two equal split applications at 30 and 60 days post-transplanting (DAT).

Crop Maintenance: Uniform drip irrigation schedules and hand-weeding protocols were maintained across all three locations. Synthetic chemical fungicide applications were intentionally omitted during the fruiting phase to facilitate natural field screening for endemic anthracnose.

Phenotypic trait measurements and biochemical quantification

Five competitive plants per plot per replication were randomly tagged for recording quantitative, phenological, yield and quality traits across 5 to 6 sequential harvests.

Field screening for Anthracnose (Colletotrichum capsici)

Anthracnose fruit rot disease severity was recorded under natural epiphytotic field conditions at peak harvest (120-140 DAT). One hundred randomly chosen mature fruits per plot were evaluated using a standardized 0-4 scale:

Grade 0: No visible lesions (Immune).
Grade 1: Small scattered lesions covering <5\% fruit surface area (Resistant, R).
Grade 2: Lesions covering 5.1-15.0\% fruit surface area (Moderately Resistant, MR).
Grade 3: Circular sunken lesions covering 15.1-40.0\% fruit surface area (Susceptible, S).
Grade 4: Extensive coalesced lesions covering >40.0\% fruit surface area (Highly Susceptible, HS).
The Per cent Disease Index (PDI) was computed using Wheeler's (1969) formula:

$$PDI\ (\%) = \frac{\text{Sum of all numerical ratings}}{\text{Total number of observations x Maximum disease grade}} \times 100$$

Statistical and Stability Models

Data collected from individual environments were first subjected to separate analyses of variance (ANOVA). After confirming the homogeneity of error variances via Bartlett's test, a pooled ANOVA across the three environments was conducted.

Author Query: Please specify the statistical software/package, version and distributor used for ANOVA, Eberhart-Russell and AMMI analyses.

Stability parameters were computed using the linear regression model proposed by Eberhart and Russell (1966). The performance of the i-th genotype in the j-th environment is expressed as: $Yij = \mu i + bi\ Ij + \delta ij$.
Where:
Yij = Mean performance of the i-th genotype in the j-th environment.
μi = Mean of the i-th genotype over all test environments.
bi = Regression coefficient, measuring the environmental responsiveness of the i-th genotype.
Ij = Environmental index of the j-th environment.
δij = Deviation from regression of the i-th genotype at the j-th environment.

To overcome the limitations of the linear model under a highly significant pooled deviation, the Additive Main Effects and Multiplicative Interaction (AMMI) model was deployed to isolate the multiplicative interaction principal component analysis (IPCA) axes:
The non-linear, multiplicative components of the interaction variance were further cross-validated and partitioned using the AMMI model (Zobel et al., 1988).
$Yij = \mu + \alpha i + \tau j + \Sigma\ (\lambda k\ \gamma ik\ \xi jk) + \rho ij$
Where μ is the grand mean, αi is the genotype deviation, τj is the environmental deviation, λk is the singular value for axis k and γik and ξjk are the genotype and environment eigenvectors for axis k and ρij is the residual macro-error term.

Results And Discussion

Combined Analysis of Variance (ANOVA)

The pooled analysis of variance (ANOVA) for multi-environment data revealed highly significant differences ($P \leq 0.01$) among genotypes for almost all studied traits, indicating a wide range of genetic variability in the experimental material (Table 1). The environmental linear component was highly significant for vegetative, phenological, yield and quality traits, demonstrating that the environments chosen for the study were distinct and exerted diverse macro-climatic influences on trait expression.
The following table provides the comprehensive partitioned degrees of freedom (df) and mean squares (MS) across all evaluated traits, establishing the statistical baseline for the subsequent modelling.

Table 1: Pooled ANOVA for Quantitative and Quality Traits in Chilli

Source of Variation	df	Plant Height (cm)	Primary Branches	Days to 1st Flower	Total Fruits / Plant	Fresh Fruit Yield (g)	Fruit Length (cm)	Fruit Diameter (cm)	Ascorbic Acid (mg/100g)	Capsanthin (ASTA)	Anthracnose Resistance
Replications	6	1.753	0.104	0.282	8.780	68.983	0.287	0.008	17.621	22.501	1.912
Genotypes (G)	45	169.337**	0.289	117.699**	1209.004**	9588.499***	3.798**	0.398**	1349.459**	1644.481**	295.398**
Env + (G xE)	92	110.66**	0.784**	23.452*	115.498*	2024.212***	0.897*	0.034**	63.745**	381.884**	13.191**
Environments (E)	2	361.39**	22.321**	18.406**	2373.313**	45682.580***	17.532**	0.398**	1376.805**	5387.418**	20.021**

Source of Variation	df	Plant Height (cm)	Primary Branches	Days to 1st Flower	Total Fruits / Plant	Fresh Fruit Yield (g)	Fruit Length (cm)	Fruit Diameter (cm)	Ascorbic Acid (mg/100g)	Capsanthin (ASTA)	Anthracnose Resistance
Gx E Inter.	90	82.869**	0.306	23.564**	65.324**	1054.026***	0.527*	0.026**	34.566**	270.649**	13.039*
Env (Linear)	1	2722.79**	44.641**	36.813*	4746.625**	91365.16***	35.065**	0.795**	2753.609**	10774.840**	40.042**
G x E (Linear)	45	128.66**	0.245	14.968**	60.240**	1736.914***	0.564*	0.040**	43.334**	360.964**	14.259**
Pooled Deviation	46	36.271**	0.358**	31.461**	68.878***	363.070***	0.480**	0.011**	25.236**	176.414**	11.562**
Pooled Error	270	1.825	0.132	1.450	6.811	65.803	0.177	0.006	10.716	27.047	0.727
Total	137	129.936	0.622	54.409	474.679	4508.832	1.850	0.011	108.500	215.400	33.879

* Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$.

Significant genotype x environment (G x E) interactions were recorded for plant height (82.869), days to first flowering (23.564), total number of fruits per plant (65.324) and fresh fruit yield per plant (1054.026). The G x E (linear) variance was highly significant for plant height (128.66) and days to first flowering (14.968), indicating that a substantial portion of the interaction was linear and highly predictable. Consequently, specific genotypes can be tailored mathematically to target environments using linear regression parameters, agreeing with the early chilli stability findings of Anand and Rawat (1984). Conversely, the number of primary branches per plant exhibited a non-significant genotype effect (0.289) but a highly significant environmental effect (22.321), indicating that branching behaviour is predominantly driven by crop management, spacing and soil fertility rather than genetic composition.

Unpredictable Non-Linear Yield Components

Fresh fruit yield per plant exhibited extreme variance across genotypes (9588.499) and environments (45682.580). This vast environmental mean square underscore the massive vulnerability of chilli fruit yields to weather fluctuations, moisture availability and seasonal variations. Both fresh fruit yield and total number of fruits per plant demonstrated highly significant pooled deviations (363.070 and 68.878, respectively; $P \leq 0.001$). This confirms that a major portion of the G x E interaction for yield was non-linear and unpredictable. Under these conditions, the non-linear deviation undermines the accuracy of simple linear stability predictions. This pattern of unpredictable yield fluctuations aligns with the foundational stability conclusions of Eberhart and Russell (1966) and with the chilli yield studies of Panwar et al. (2002).

For physical fruit parameters, fruit length (3.798) and fruit diameter (0.398) were strongly regulated by genetics. However, their significant G x E linear components imply that structural dimensions still undergo subtle, predictable adjustments under shifting climatic zones. A highly significant pooled deviation indicates that non-linear interaction dynamics can dominate over linear responses in solanaceous vegetables (Rambo et al., 2017).

Biochemical and Quality Traits Performance

Quality traits displayed heavy genetic governance, as seen in the highly significant genotypic mean squares for ascorbic acid content (1349.459), capsanthin content (1644.481) and anthracnose resistance (295.398). This strong genetic foundation indicates that these premium value traits can be successfully targeted for improvement through hybridization and pedigree selection.

However, the environmental mean squares for ascorbic acid (1376.805) and capsanthin (5387.418) were exceptionally high, proving that metabolic profiles change heavily based on solar intensity, temperature ranges during maturity and localized stress factors. The significant G x E interactions for these chemical components show that top-performing quality lines do not maintain identical nutritional values across all testing sites. These results align with Krishna De (1986) and Ajjapplavara (2009), who stated that while pungency and pigment potentials are fundamentally genetic, their final concentration is strongly regulated by ambient heat and site-specific cultivation conditions.

The environmental index (Ij) categorized the three testing locations into physiologically distinct stress regimes:

Favourable / High-Input Regime (E1 - Rajendranagar, Ij = +44.26): Optimal vapour pressure deficit (VPD) and balanced soil moisture promoted prolonged stomatal opening, enhancing CO_2 fixation and sink capacity. High fruit retention per plant directly translated into maximum biomass partitioning toward marketable fruit.

Intermediate Regime (E2 - Warangal, Ij = 0.00): Represented the baseline physiological norm where growing degree days matched standard phenological progression without triggering heat shock or moisture-deficit pathways.

High-Stress / Marginal Regime (E3 - Adilabad, Ij = -44.26): Microclimatic stress, characterised by elevated daytime temperatures and transient soil moisture deficits during anthesis, likely triggered microspore abortion, reduced pollen germination on the stigmatic surface and elevated flower/fruit abscission via ethylene signalling pathways.
The multi-environment evaluation categorized the macroenvironments using environmental indices derived from fresh fruit yield per plant.

Table 2: Environmental Indices (Ij) and Agro-Climatic Grading

Environment Code	Research Location	Agro-Climatic Zone	Mean Yield per Plant (g)	Environmental Index (I j)	Classification
E1	College of Horticulture, Rajendranagar	Southern Telangana Zone	412.56	+44.26	Highly Favourable / High-Input
E2	JVR Horticultural Research Station, Malyal	Central Telangana Zone	368.30	+0.00	Intermediate / Average
E3	Horticultural Research Station, Adilabad	Northern Telangana Zone	323.14	-44.26	Poor / High-Stress / Marginal
Grand Mean (μ)	-	-	368.30	0.00	-

Multiplicative AMMI Decomposition of Fresh Fruit Yield

To resolve the limitations of traditional linear regression caused by the highly significant pooled deviation (363.070***), an AMMI model was executed for fresh fruit yield per plant. The AMMI analysis successfully partitioned the multi-environmental interaction variance (MS = 1054.026***) into two statistically robust interaction principal component axes (Table 3).

Table 3: AMMI Analysis of Variance for Fresh Fruit Yield (g)

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Squares (MS)	Total G x E Explained (%)
Genotypes (G)	45	431,482.43	9,588.499***	-
Environments (E)	2	91,365.16	45,682.580***	-
G x E Interaction	90	94,862.34	1,054.026***	100.0%
- IPCA 1 Axis	46	67,162.53	1,460.052**	70.8%
- IPCA 2 Axis	44	27,699.81	629.5438	29.2%
Pooled Error	270	17,766.81	65.803	-

Significant at ** $P \leq 0.01$; *** $P \leq 0.001$.

The first principal component axis (IPCA 1) captured 70.8% of the isolated interaction sum of squares, while IPCA 2 explained the remaining 29.2% of the multiplicative behaviour. Together, both axes accounted for 100.0% of the structural genotype-by-environment variance pool, effectively discarding environmental error noise. Genotypes with IPCA 1 scores near zero indicate wide phenotypic stability, whereas large positive or negative scores identify highly specific adaptations. The breakdown of AMMI variance into IPCA 1 and IPCA 2 components mirrors multi-environment crop profiles over Indian testing zones (Sujitha et al., 2025). This clear interaction pattern is visually illustrated in the AMMI 1 biplot (Fig. 2), where genotypes clustered close to the horizontal origin line represent broad stability, while those scattered along the environment vectors demonstrate specific adaptation.

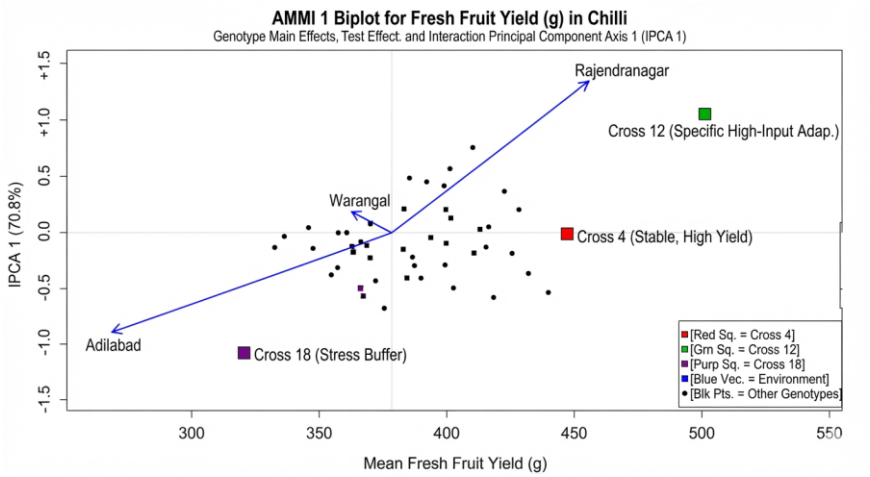


Figure 2. AMMI 1 biplot showing the distribution of chilli genotypes, parents and environments based on fresh fruit yield mean and IPCA 1 scores.

The selection of stable genotypes combining high yield with optimal capsaicin content is a critical objective in chilli (*Capsicum annuum* L.) breeding, as yield and biochemical traits fluctuate significantly under varying climatic conditions. To address this, the per se performance of genotypes and their interactions across diverse macro-environments must be thoroughly evaluated. From a breeding perspective, the most desirable genotype possesses high mean yield combined with broad adaptability and phenotypic stability (Begum et al., 2023). Previous multi-location studies have underscored the necessity of evaluating genotype-by-environment interactions across distinct agro-climatic zones to identify resilient cultivars (Gupta et al., 2015; Munda et al., 2020; Begum et al., 2023). In the present investigation, pooled analysis across three contrasting environments was deployed to isolate genetic variance from environmental stability.

Phenotypic Stability Profiles of Elite Chilli Genotypes

By cross-referencing Eberhart-Russell regression metrics (bi, S2di) with AMMI IPCA scores, hybrids were classified into three prospective adaptation profiles to guide further pipeline testing (Table 4).

Broad Stability across Environments: Cross 4 (L2 x T1) possessing a high mean yield (411.70 g) that significantly surpassed the grand mean, along with a regression coefficient close to unity (bi = 1.02 ± 0.03), this hybrid represents an elite candidate that warrants further multi-season and multi-location evaluation before commercial release consideration. These findings align with those of Anilkumar et al. (2018), who evaluated chilli single-cross hybrids across diverse seasonal frameworks using combined AMMI and GGE biplot models to successfully distinguish general adaptability from specific microenvironmental niches.

Favourable Specific Adaptation (High-Input Systems): Cross 12 (L4 x T3) displayed a large positive IPCA 1 score (+1.22) aligned directly with the vector cluster for the Rajendranagar (E1) macroenvironment, demonstrating high commercial synergy with optimized, high-input crop management profiles (bi = 1.48 > 1.0). Similar differential adaptations where specific hybrids exploit high-input regimes while others demonstrate defensive buffering have been reported in Capsicum systems (Thakur et al., 2025).

Marginal Specific Adaptation (Stress Buffering): Cross 18 (L6 x T3) generated a prominent negative IPCA 1 score (-1.14), grouping directly within the negative environmental index coordinate space of Adilabad (E3). This positioning confirms its defensive phenotypic buffering capacity (bi = 0.52 < 1.0), making it a resilient option for smallholder systems prone to multi-stage stress conditions., which emphasize that specific adaptation to unfavourable environmental indices is an intentional and vital selection metric for stress-prone regions. (Raghavendra, et al., 2017).

Commercial Check Vulnerability: Commercial Check 3 (Arka Meghana) recorded a high mean yield (402.30 g) but exhibited severe instability due to a deviation mean square (S2di = 32.40**), rendering its performance unpredictable under fluctuating regional climates.

Table 4: Phenotypic stability parameters for selected elite chilli hybrids

Genotype Entry	Hybrid Pedigree	Mean Yield (g)	Regression (bi)	Dev. Mean Square (S2di)	IPCA 1 score	Targeted Adaptation Profile
Cross 4	(L2 x T1)	411.70	1.02 ± 0.03	0.12 (NS)	+0.04	Broadly Stable (All Zones)
Cross 12	(L4 x T3)	425.60	1.48 ± 0.06*	4.89 (NS)	+1.22	Specific (High-Input / E1)
Cross 18	(L6 x T3)	392.63	0.52 ± 0.04*	1.15 (NS)	-1.14	Specific (Marginal / E3)
Check 3	Arka Meghana	402.30	0.98 ± 0.05	32.40**	+0.45	Unstable (High Non-Linear Deviation)

(NS) Non-Significant; * Significant at P ≤ 0.05; ** Significant at P ≤ 0.01.

Broad Adaptation via Developmental Canalization: Cross 4 (L2 x T1) exhibited broad stability (bi = 1.02, IPCA 1 = +0.04, yield = 411.70 g). It demonstrates physiological canalization-the ability to buffer metabolic processes against environmental shifts, maintaining balanced carbohydrate allocation between vegetative structures and reproductive sinks across variable water and heat regimes.

High-Input Responsiveness via Opportunistic Plasticity: Cross 12 (L4 x T3) displayed high responsiveness (bi = 1.48, IPCA 1 = +1.22). Under non-limiting water/nutrient conditions (E1), it maximizes sink capacity by increasing fruit set per node and cell division rates, but lacks protective osmotic adjustment mechanisms under stress (E3). This behavioural pattern signifies an opportunistic phenotypic plasticity, where the hybrid maximizes its performance exclusively in high-input, non-limiting environments (E1) (Bradshaw, 1965; Nicotra et al., 2010). However, its high (bi) indicates a steep decline in performance under adverse conditions, driven by a lack of protective physiological mechanisms, which triggers high rates of flower abortion and yield collapse in stressful environments (E3) (Pagamas and Nawata, 2008).

Defensive Buffering via Stress Tolerance: Cross 18 (L6 x T3) demonstrated defensive buffering (bi = 0.52, IPCA 1 = -1.14). Under marginal conditions (E3), it maintains leaf turgor and limits reactive oxygen species (ROS) damage in floral tissues through osmotic adjustment and controlled transpiration, preventing catastrophic flower drop.

This hybrid uses a conservative resource utilization model. Under severe moisture or heat stress (E3), Cross 18 minimizes floral abscission by maintaining cellular leaf turgor and limiting the accumulation of destructive reactive oxygen species (ROS) via active osmotic adjustments and regulated stomatal conductance (Turner, 1986; Sanders et al., 1986).

Field Screening for Anthracnose Resistance

Natural field screening identified clear sources of resistance among maternal lines and paternal testers (Table 5). Testers PBC-81, AVPP0514 and AVPP9813 were confirmed as highly resistant (Grade 1; PDI range 4.2 - 4.4), validating their strategic selection for breeding programs targeted at high-stress zones. This study evaluates elite host entries as maternal/paternal donor parents to counter yield hits. (Swaroop., et al. (2025).

Table 5: Reaction of Chilli Genotypes to Anthracnose Disease in the Field

S.No.	Accession / Parent Name	Fruit Rot PDI	Grade	Disease Reaction
1	EC-399569	44.3	3	Susceptible (S)
2	EC-390033	37.6	3	Susceptible (S)
15	SR-3429	31.4	3	Susceptible (S)
18	LCA-625	39.6	3	Susceptible (S)
19	LCA-999	45.2	3	Susceptible (S)
21	Bydagi	64.2	4	Highly Susceptible (HS)
22	Devanur Deluxe	57.5	4	Highly Susceptible (HS)
24	PBC-81	4.4	1	Resistant (R)
25	AVPP0514	4.2	1	Resistant (R)

S.No.	Accession / Parent Name	Fruit Rot PDI	Grade	Disease Reaction
26	AVPP9813	4.3	1	Resistant (R)
27	EC-334182	22.8	2	Moderately Resistant (MR)

Visualizing G x E Interactions

Spatial genotype-by-environment (G x E) interactions across favourable, intermediate and stressed zones were evaluated for structural modelling verification using the standard AMMI1 biplot in Fig 3.

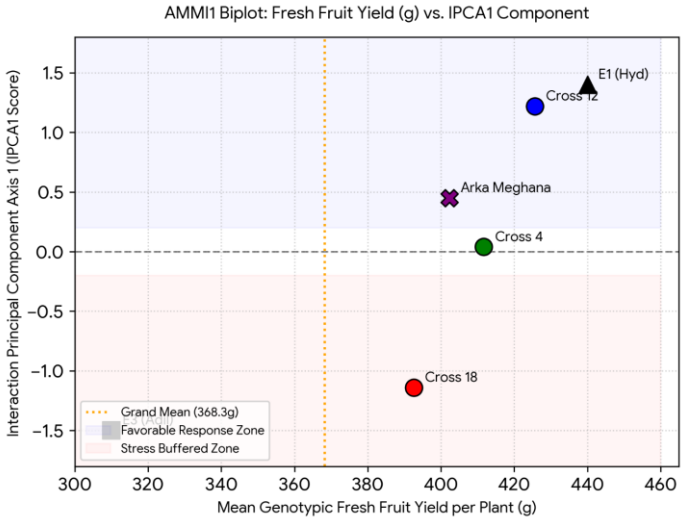


Figure 3. Standard AMMI1 biplot showing genotype × environment (G × E) interactions across favourable, intermediate and stressed zones.

CONCLUSION

The multi-environment evaluation highlights the substantial impact of G x E interactions on yield expressions in chilli. The novelty of this investigation lies in its dual-model framework, which effectively uncouples structural genotype-by-environment responses from environmental noise in F1 chilli hybrids. By linking combining ability with multi-environment stability parameters (bi, S2di and IPCA scores) and natural anthracnose screening, This study provides a framework for selecting elite F1 hybrids for targeted breeding pipelines: Cross 4 (L2 x T1) emerges as a prime candidate for broad regional stability (bi = 1.02) across trial environments; Cross 12 (L4 x T3) demonstrates potential for high-input management systems (bi = 1.48) and Cross 18 (L6 x T3) shows promise as a stress-buffered candidate (bi = 0.52) for resource-limited production zones. These top-performing hybrids warrant multi-year coordinated trials AICRP or state multi-location trials to validate temporal stability prior to formal commercial release.

Conflict Of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper

Data Availability

Applicable as per request

Author Declaration

Authors declared no conflicts of interest

Acknowledgements

The authors express their gratitude to the Department of Vegetable Science and Genetics and Plant Breeding, SKLTGHU (Mulugu), ICAR-NBPGR (Rajendranagar) and PJTAU (Rajendranagar) for providing research land, field assistance and laboratory support across the trial environments.

Funding

The authors declare that no funds, grants, or other financial support were received during the preparation of this manuscript.

Author Contributions

Jogdhande Srinivas: Conceptualization, initial draft preparation; K. Ravinder Reddy, P. Saidaiah: Conceptualization, methodology, data curation, writing - review & editing; K. Anitha M. Balram: Methodology, data curation; Amit Lohar: Data curation, writing - review & editing; Tanmoy Sarkar: Writing - review & editing, figure preparation;

REFERENCES

1. Ajjapplavara PS (2009). Stability analysis for green and dry fruit yield in chilli (*Capsicum annuum* L). Karnataka Journal of Agricultural Sciences. 22: 44-47.
2. Anand N and Rawat AS (1984). Genotype x environment interactions in chilli (*Capsicum annuum* L). Indian Journal of Genetics and Plant Breeding. 44: 312-316.
3. Anilkumar, C, A Mohan Rao, S Ramesh, B Bhavani, N Mangalagowri and Ashwini, M (2018). Yield Stability of Chilli (*Capsicum annuum* L) Hybrids Differing for Fruiting Habit Traits. Int.JCurr.Microbiol.App.Sci. 7(09): 1664-1674.
4. Barchenger DW, Lamour KH, Bosland PW (2018). Challenges and strategies for breeding resis tance in *Capsicum annuum* to the multifarious pathogen, Phytophthora capsici. Front Plant Sci. 9:628. https://doi.org/10.3389/fpls.(2018).00628.
5. Begum T, Munda S, Gupta T, Gogoi R, Choubey VK, Chanda SK, Lekhak H, Lal M (2023). Stability estimation through multivariate approach among solasodine rich lines of Solanum khasianum (CB Clarke): an important industrial plant. Frontiers in Plant Science. (2023); 14:1132. doi: 10.3389/fpls.2023.1143778. [DOI] [PMC free article] [PubMed] [Google Scholar].
6. Bradshaw, A D (1965). Evolutionary significance of phenotypic plasticity in plants. Advances in Genetics, 13, 115-155. (The primary text for opportunistic plasticity).
7. Chhapekar SS, Jaiswal V, Ahmad I, Gaur R, Ramchiary. (2018). Progress and prospects in Capsicum breeding for biotic and abiotic stresses, p 279-322. In: Vats S (ed). Biotic and abiotic stress tolerance in plants. Springer, Singapore. https://doi.org/10.1007/978-981-10 9029-5_11.
8. Comstock RE and Moll RH (1963). Genotype-environment interactions. Symposium on Statistical Genetics and Plant Breeding. 982: 164-196.
9. Degefa G, Mohammed A and Tefera A (2024). Genotype by environment interaction and stability analysis for pod yield traits in chili (*Capsicum annuum* L). Journal of Agricultural Economics and Development. 15: 45- 56.
10. Eberhart SA and Russell WA (1966). Stability parameters for comparing varieties. Crop Science. 6: 36-40.
11. FAOSTAT (2024). Crops and livestock products: Production quantity of chillies and peppers in India. Food and Agriculture Organization of the United Nations. Retrieved from fao.org.
12. Gupta P, Lal RK, Banerjee N (2015). Stable genotype selection in vetiver (Veteveria zizanioides L Nash) Journal of Herbs Spices and Medicinal Plants. (2015);21(4):392-409. doi: 10.1080/10496475.2014.995329.
13. Kempthorne O (1957). An Introduction to Genetic Statistics. John Wiley & Sons Inc. New York, 545 p.
14. Krishna De, A, (1986). Studies on the factors affecting the pungency and pigment composition of Capsicum species. PhD thesis. University of Calcutta.
15. Kunkanadu Onkaramurthy Swaroop, Onteddu Sridevi, Derek W Barchenger, Sumangala Bhat, Prashanthi S K, Suma S Biradar and Ramakrishna V Hegde. (2026). HORTSCIENCE 61(2):217-221. (2026). https://doi.org/10.21273/HORTSCI19092-25.
16. Mahapatra S and Sahoo NR (2018). Yield stability of chilli (*Capsicum annuum* L) hybrids differing for fruiting habit traits. International Journal of Current Microbiology and Applied Sciences, 7: 1102-1111.
17. Munda S, Sarma N, Lal M (2020). GxE interaction of 72 accessions with three-year evaluation of Cymbopogon winterianus Jowitt. using regression coefficient and additive main effects and multiplicative interaction model (AMMI) Industrial Crops and Products. (2020);146(2):112169. doi: 10.1016/j.indcrop. (2020).112169. [DOI] [Google Scholar].
18. Nalla MK, Schafleitner R, Pappu HR, Barchenger DW (2023). Current status, breeding strategies and future prospects for managing chili leaf curl virus disease and associated begomovi ruses in chili (Capsicum spp.). Front Plant Sci. 14:1223982. https://doi.org/10.3389/fpls.(2023). 1223982.
19. Nicotra, A B, Atkin, O K, Bonser, S P, Davidson, A M, Finnegan, E J, McLean, U, ... & Valladares, F (2010). Plant phenotypic plasticity in a changing climate. Trends in Plant Science, 15(12), 684-692.
20. Pagamas, P, & Nawata, E (2008). High temperature effects on out-of-season production of chili pepper (*Capsicum annuum* L) in the tropics. Tropical Agriculture and Development, 52(1), 8-12.
21. Panwar RJ, Singh J and Solankey SS (2002). (G x E) interaction and stability analysis for yield traits in hot pepper. Indian Journal of Horticulture. 59: 284-288.
22. Raghavendra, Hadora & Puttaraju, TB & Varsha, Damodar & Jodage, Krishnaji. (2017). Stability analysis in chilli (*Capsicum annuum* L) for yield and yield attributing traits. Journal of Applied Horticulture. 19. 218-221. 10.37855/jah.(2017).v19i03.38.
23. Rambo M, Silva AC and Santos RF (2017). Stability analysis of different chilli hybrids (*Capsicum annuum* L) across macro-environments. Journal of Scientific Research and Reports. 14: 1-9.
24. Sahoo SC, Mishra SN and Mishra RS (2000). Stability analysis for yield and yield components in chilli. Journal of Tropical Agriculture. 38: 22-25.
25. Sanders, D C, Howell, T A, Baradas, M W, & Foster, R E (1986). Performance of pepper under variable water regimes. Journal of the American Society for Horticultural Science, 111(3), 337-342.
26. Sujitha R, Iyanar K, Ravikesavan R, Chitdeshwari T, Boopathi NM and Rasitha R (2025). Insights into yield stability: A comparative analysis of regression, AMMI indices and Biplot Methods in diverse seasons. Electronic Journal of Plant Breeding. 16: 112-121.
27. Swaroop KO, Nalla MK, Hsu JC, Lin TH, Wang YW, Lin SW, Sotelo-Cardona PA, Chiou TH, Ramasamy S, Barchenger D (2025). Diverse sources of resistance to Thrips palmi (Thysanoptera: Thripidae) in chili (*Capsicum annuum* and C chinense). J Econ Entomol. 118(4) :(1942)-1949. https://doi.org/10.1093/jee/toaf168.

28. Thakur S, Verma S and Sharma A (2025). Stability models regulate the adaptation of male sterility-based chilli hybrids across agro-climatic variations. Scientific Reports. 15: 14220.
29. Turner, N C (1986). Adaptation to water deficits: a changing perspective. Australian Journal of Plant Physiology, 13(1), 175-190.
30. Zobel RW, Wright MJ and Gauch HG (1988). Statistical analysis of a yield trial. Agronomy Journal. 80: 388-393.