Biological Forum – An International Journal 13(3): 249-254(2021)

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

Genotype × Environment Interaction and Fruit Yield Stability in Tomato Hybrids under Kashmir Valley conditions using Additive Main Effects and Multiplicative Interaction (AMMI) Model

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(Received 15 June 2021, Accepted 02 August, 2021)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Tomato is the second most important vegetable crop in the world due to its significant nutritive value. The yield and quality of the fruits are highly influenced by the environment due to a phenomenon known as genotype by environment (G × E) interaction which confounds selection efficiency. Hence, plant breeding requires a multi-environment study to analyze the response of genotypes to different conditions. At three locations in Kashmir valley *viz*., Experimental fields of the Division of Vegetable Science, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir, Krishi Vigyan Kendra (KVK), Malangpora, and Regional Research Station & Faculty of Agriculture (RRS & FOA), Wadura over two years, seventeen tomato hybrids (*Solanum lycopersicum* Mill.) were examined with the goal of comparing yield performance and assessing adaptation using Additive Main Effects and Multiplicative Interaction model (AMMI). The three locations are designated as E_1, E_2 and E_3 respectively for first year and E4, E5, E6 respectively for second year. The study was set up in a randomized block design, with three replications at each location. Shalimar tomato hybrid-2 had the highest fruit yield (908.845 q/ha) across all locations and years, while Arth-3 had the lowest yield (381.296q/ha). Environments (E), genotypes (G) and G × E interaction (GEI) all had significant main effects (p<0.01), with genotype effects accounting for the most variation (62.617%). The first three Interaction Principal Component Axes (IPCA1, 2 and 3) were statistically significant (p<0.01) and accounted for 98.139% of the total GEI. The biplot revealed thatH3 and 7 (Shalimar tomato hybrid-1, PS-255) are the most stable and yield the highest, while H4 and H12 (Shalimar tomato hybrid-2, Bhaskar Improved) are less stable but yield the highest. H9 and 17 (Ajeet and Swaraj-1516) were the best adapted hybrids to most environments, with IPCA values near to zero, showing their stability across all environments. A biplot of the first two IPCA shows that H9 and 17 (Ajeet and Swaraj-1516) were the best suited hybrids to most environments, with IPCA values close to zero, demonstrating their stability across all the environments. Overall the data generated from this particular trial gives an estimation and prediction of yield, determines yield stability and the pattern of genotypic response across environments; and at last provides reliable guidance for selecting the best genotypes for planting in future years and at new areas.

Keywords: Biplot, Tomato, Stability, AMMI analysis, PCA

INTRODUCTION

Tomato (*Solanum lycopersicum* L., 2n=24) belongs to family Solanaceae and is largely cultivated in temperate and tropical climates around the world. Due to its widespread consumption and numerous usages, it outperforms all other vegetables in terms of total contribution of vital nutrients to the diet (Nwosu *et al*., 2014). It is thought to have originated in Peru-Ecuador (Rick, 1969). Tomatoes are grown as a summer crop in Kashmir, and fresh tomatoes are only available for a few months due to climatic conditions that are only favourable for fruit set and ripening in late summer. The lack of high yielding genotypes is a key constraint in increasing this crop's production and productivity in Kashmir valley. In view of the significance, it is necessary to produce genotypes with higher production and quality. Despite the fact that a number of hybrids have been proposed for cultivation, information on their stability in Kashmir's agro-climatic conditions is scarce. As a result, it is necessary to examine and screen possible genotypes that provide consistent performance across multiple years, as well as to choose genotypes based on stability parameters for key yield and maturity characters (Kalloo *et al.*, 1998). One of the main causes of low production is the unpredictable performance of released varieties and hybrids. Hence, it is critical to find a hybrid that not only has a high yield potential but also has a consistent performance under different climatic conditions. Genotype × Environment (GE) interaction is valuable for explaining adaptation patterns, as only this interaction can be utilised by choosing for explicit adaptation or by developing explicitly adapted genotypes. The G×E interactions of the germplasm are vital to avoid genetic vulnerability linked with the narrowing of any crop's genetic base (Kang, 1998).

Several statistical approaches for analysing Genotype × Environment Interactions (GEI) have been developed (Flores *et al*., 1998). Regression technique has been widely used (Eberhart and Russel, 1966) due to its simplicity and the fact that its information on adaptive responses is easily applicable to locations (Annicchiarico, 1997). The principal component analysis (PCA) method that shows the mean squares of the principal components axes (Gauch and Furnas, 1991) has also been used. AMMI (additive main effects and multiplicative interaction) has been shown to be an effective way for illustrating adaptive responses (Ariyo, 1999). It's commonly employed in field studies when both the major effects and the interactions between them are essential. AMMI model has been used in recent times due to the fact that it combines the classical additive main effects model for G × E interaction with the multiplicative components into an integral least square analysis which has led to its effectiveness in selection of stable genotypes (Ariyo and Ayo-Vaughan 2000). It fits the additive main effect of genotypes and environments using analysis of variance and then describes the non-additive parts and the GEI using principal component analysis (PCA) (Osekita *et al.,* 2019). Using the first interaction principal component axis (IPCA1) and the mean yields, the model generates a biplot. Genotypes, locations and environments, as well as their interactions, are obtained using this biplot. Very less work on stability studies in tomato using the AMMI model has been done so far, one among the few being the work of Akinyode *et al.*, 2020. To fill this research gap also, the AMMI model was used in this particular experiment to analyze the yield data of 16 tomato hybrids in three environments over the course of two years.

MATERIALS AND METHODS

Plant materials: The experimental material used in the present study comprised of seventeen tomato hybrids. The seeds were obtained from the Division of Vegetable science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, as well as some private vegetable seed dealers.

Field trials: The current study was conducted in three locations in Kashmir valley over a course of two years to assess performance and stability of tomato hybrids. The random locations selected were: Experimental fields of the Division of vegetable science, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir, Krishi Vigyan Kendra (KVK), Malangpora, and Regional Research Station & Faculty of Agriculture (RRS & FOA), Wadura. The three locations are referred to as E_1, E_2 and E_3in this study. The experiment was conducted in a randomized block design with three replications per location. Each replication comprised of 4 rows each having 3 plants, spaced at 60×45 cm. The experimental fields were well prepared, and standard recommended package of practices for raising a healthy crop were followed.

Statistical analysis: The AMMI model was used with additive effects and a multiplicative term for GEI, based on data collected on fruit yield for 17 tomato hybrids and six testing conditions. The AMMI analysis first fits additive effects for host genotypes and environments using standard additive ANOVA, and then multiplicative effects for G×E (genotype × environment) using principal component analysis. The AMMI model is:

$$Y_{ij} = \mu + g_i + e_j + \sum_{k=1}^{n} \lambda_k \alpha_{ik} \gamma_{jk} + e_{ij}$$

where Y_{ij} is the yield of the i_{th} genotype in the j_{th} environment, g_i is the i_{th} genotype mean deviation, e_j is the j_{th} environment mean deviation, λ_k is the square root of the eigen value of the PCA axis K, α_{ik} and γ_{jk} are the principal component scores for PCA axis k of the i_{th} genotype and the j_{th} environment, respectively, and ε_{ij} is the residual. PCA scores for the environment and genotype are expressed as unit vectors multiplied by the square root of λ_k, i.e., PCA score for the environment = λk0.5 yik and PCA score for the genotype = λk0.5 αik (Zobel *et al.,* 1988). AMMI analysis was performed on the experimental data using software developed by Indostat Ltd. in Hyderabad.

RESULTS AND DISCUSSION

A. AMMI model analysis of variance for yield

The additive main effect and multiplicative interaction(AMMI) model analysis for fruit yield in seventeen tomato hybrids tested across 6 environments (3-locations by 2- years) is presented in Table 1. The result revealed that, genotype(G), environment (E) and genotype-by-environment (G × E) interaction were all highly significant at ($p < 0.01$) showing that there was a large range of variation between genotypes, locations, and their interactions, accounting for 62.617%, 34.052% and 3.331% of the total variation, respectively. Similar results have also been obtained in tomato genotypes by Ketema *et al., (*2017) and Netsanet *et al.,* (2018). Because genotypes contributed the most to yield variation, the inherent genetic component for yield was the most important source of variation (Fiseha *et al*., 2014). The genotype effect was over nineteen times greater than the GEI, implying the possibility of many genotype groups (Mohammadi *et al*., 2011). The effect of environments on GEI, genetic variability among hybrids, and the possibility of selecting stable hybrids were all revealed by significant differences in genotypes, environments, and GEI. The interaction component yields three significant ($p < 0.01$) IPCAs, according to AMMI model. The retrieved IPCAs have the ability to provide information about GEI effect. The first principal component axis (IPCA1), which was significant and accounted for 64.578% of the sum of squares in 20 interaction degree of freedom (df), explained the majority of the total sum of squares due to G × E interaction. IPCA 2 and IPCA3 were also significant, accounting for 24.676% and 8.885% of the GEI sum of squares, respectively, with 18 and 16 degrees of freedom. They cumulatively captured 98.139% of the total GEI SS, using 54 df. This meant that the interactions of the 17 tomato hybrids tested in six environments were anticipated by the first three principal genotype and environment components. This was in accordance with the study of Bose *et al.*, (2014). From the first to the third IPCA, the score of the IPCAs declines; yet, the first two IPCAs could best explain the interaction sum of squares (Zobel *et al.*, 1988).

Table 1: Combined analysis of variance (ANOVA) according to the AMMI model for Yield/ ha (q) of Tomato Hybrids.

Source	Df	Sum of square	Mean squares	Total variation explained (%)
Genotypes	16	2325424.407	145339.025**	62.617
Environments	5	1264605.979	252921.196**	34.052
G x E interaction	80	123693.613	1546.170**	3.331
IPCA I	20	79879.334	3993.967**	64.578
IPCA II	18	30522.568	1695.698**	24.676
IPCA III	16	10989.888	686.868**	8.885
Residual	26	301.823	88.532	--

B. IPCAs crossover and non-cross over interaction

Principal components analysis (PCA) based on rank correlation matrix was utilised to better understand the correlations, similarities, and differences among the yield-stability statistics. Both positive and negative values were found in the IPCA genotype and environment scores (Table 2 & 3). A genotype with a high positive IPCA score in some locations must have a high negative IPCA score in other locations. As a result, these scores showed a disproportionate genotype response (Yan and Hunt, 2001), which was the most significant source of variation in any crossover (qualitative) interaction. Crossover GEI refers to the unequal genotype response. Same sign or near zero scores, on the other hand, indicate a non-crossover (quantitative) GEI or a proportionate genotype response (Mohammadi *et al*., 2007; Mohammadi and Amri, 2008; Farshadfar, 2008).

Larger IPCA scores of hybrids indicate that they are more responsive to interaction effects and more particularly adapted to a given environment. The hybrids with lower IPCA scores, on the other hand, are less responsive to the interaction effect and are deemed widely adapted. As a result, hybrids with higher IPCA1 scores, such as H1; TH-670 (7.94), H2; TH-1389 (6.35), H12; Bhaskar Improved (5.87), H5; TO-687 (5.62), and H7; PS-255 (4.86), might be classified as specifically adapted while as hybrids with lower IPCA1 scores, such as H9; Ajeet (0.63), H10; Samrat 1861 (0.89), H17; Swaraj-1516 (0.96), H14; Maharaja (1.05), and H16; Yuvraj (1.18), may be deemed as widely adapted or stable.

Table 2: IPCA 1 and IPCA 2 scores for Tomato Hybrids for Yield ha^{-1} (q).

Sr. No.	Genotypes	Mean	IPCA 1 score	IPCA 2 score
1.	TH-670	591.196	7.94	-1.06
2.	TH-1389	421.994	6.35	9.22
3.	Shalimar tomato hybrid-1	864.887	-4.64	1.71
4.	Shalimar tomato hybrid-2	908.845	-3.37	5.88
5.	TO-687	698.548	-5.62	-0.61
6.	Indam-531	683.664	1.64	-1.63
7.	PS-255	867.068	-4.86	-0.20
8.	NS-2535	671.040	1.63	-1.89
9.	Ajeet	634.586	0.63	-0.57
10.	Samrat 1861	608.717	0.89	-5.32
11.	Arth-3	381.296	4.71	-2.55
12.	Bhaskar Improved	858.808	-5.87	-1.35
13.	Kanchan	582.404	1.94	-1.44
14.	Maharaja	750.893	1.05	0.31
15.	Rambo	898.972	-4.55	1.54
16.	Yuvraj	644.418	1.18	-1.69
17.	Swaraj-1516	727.710	0.96	-0.35

Table 3: IPCA 1 and IPCA 2 scores for six environments for Yield ha^{-1} (q) of Tomato Hybrids.

Environments	Mean	IPCA 1 score	IPCA 2 score
E_1	860.589	-7.75	-1.23
E_2	704.843	-0.30	1.07
E_3	575.317	2.58	11.23
E_4	805.858	-8.29	-2.06
E_5	659.113	1.77	-5.18
E_6	557.237	11.99	-3.84

This was in accordance with the study of Akinyode *et al.,* (2020). In the present investigation, among the environments evaluated in the study, only E2 had an IPCA 1 score close to zero, indicating that it will have less interaction effects.

C. Yield performance in individual environments

As shown in Table 4, the highest mean yield of all hybrids was 860.589 q/ha at E1 (Experimental fields of the Division of Vegetable Science, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir in the first year), followed by 805.858 q/ha at E4 (Experimental fields of the Division of Vegetable Science, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir in the second year) and the lowest value noted was 557.237 q/ha in E6 (Regional Research Station & Faculty of Agriculture (RRS & FOA), Wadura, second year). This demonstrated that different environments were not equally favourable or unfavourable for hybrids, with E1 proving to be the best or most favourable environment and E6 proving to be the least favourable in terms of hybrid performance.

Table 4: Mean Performance in individual environments for Yield per ha (q) in Tomato Hybrids (*Solanum lycopersicum* Mill.).

Sr. No.	Genotypes	E_1	E_2	E_3	E_4	E_5	E_6	Mean
1.	TH-670	681.313	583.243	513.967	644.913	585.430	538.307	**591.196**
2.	TH-1389	573.180	456.433	202.680	472.630	428.140	398.903	**421.994**
3	Shalimar tomato hybrid-1	1061.583	872.723	717.183	1024.933	836.067	676.830	**864.887**
4.	Shalimar tomato hybrid-2	1072.697	883.827	728.297	1101.740	912.870	753.640	**908.845**
5.	TO-687	914.190	706.810	573.500	851.990	652.020	492.780	**698.548**
6.	Indam-531	836.547	693.740	588.680	777.563	645.923	559.533	**683.664**
7.	PS-255	1076.623	887.763	735.930	1009.317	824.157	668.620	**867.068**
8.	NS-2535	826.073	680.503	577.730	767.330	623.890	550.710	**671.040**
9.	Ajeet	798.450	642.207	523.773	744.047	590.137	508.900	**634.586**
10.	Samrat 1861	754.840	659.283	540.740	703.240	530.090	464.107	**608.717**
11.	Arth-3	500.977	385.077	307.697	455.337	350.193	288.497	**381.296**
12.	Bhaskar improved	1091.210	894.940	732.000	989.320	800.457	644.923	**858.808**
13.	Kanchan	731.760	589.577	486.893	676.707	546.370	463.117	**582.404**
14.	Maharaja	915.930	749.007	634.963	853.510	722.400	629.547	**750.893**
15.	Rambo	1099.850	910.987	751.750	1052.367	867.207	711.670	**898.972**
16.	Yuvraj	802.863	649.797	549.637	744.057	602.640	517.513	**644.418**
17.	Swaraj-1516	891.930	736.413	614.963	830.590	686.930	605.433	**727.710**
Grand Mean		**860.589**	**704.843**	**575.317**	**805.858**	**659.113**	**557.237**	**693.826**
SE(±)		**21.162**	**18.482**	**17.497**	**20.794**	**19.145**	**18.291**	

D. Biplot display

The AMMI analysis generates a biplot (Fig. 1), which depicts main effects on the abscissa (x-axis) and first axis principal component analysis (IPCA1) values on the ordinate (y-axis), and contains two types of points for genotypes and environments (Zobel *et al.,* 1998). The AMMI biplot is made by plotting genotypes and environment means (main effects) on the abscissa and the IPCA on the ordinate (Kempton, 1984; Zobel, 1990). The direction and magnitude of differences between genotypes along the X-axis (yield) and Y axis (IPCA 1 scores) are necessary. Genotypes and environments that are almost perpendicular to the graph's horizontal line have similar mean yields, while those that are horizontally aligned have similar interaction patterns (Crossa *et al.,* 1990). High interactions are found in genotypes and environments with significant first IPCA scores (plus or minus); minor interactions are seen in genotypes and environments with values close to zero (Hill *et al.,* 1998) and are considered stable (Abalo, 2003). The yields of genotypes or environments present on the right side of the perpendicular line (the line that runs between 600 and 700q/ha yield) are higher than those on the left side. The analysis of biplot revealed that the hybrids (H) positioned by AMMI on the right side of the midpoint of the perpendicular line viz., H3, 4, 5, 6, 7, 8, 12, 14, 15, and 17 were generally high yielding, with H4 (Shalimar tomato hybrid-2) being the top yielder (Fig. 1). However, low yielding hybrids viz., H1, 2, 9, 10, 11, 13, and 16 were positioned on the left hand side of the midpoint of the perpendicular line on biplot, with H11 (Arth-3) being the lowest yielder. In the biplot, H3 and 7 (Shalimar tomato hybrid-1, PS-255) are most stable with high yields as well whereas H4 and H12 (Shalimar tomato hybrid-2, Bhaskar Improved) were lesser stable but had high yields. Among the environments tested in the study, the most favourable environments appeared to be E1, 2, 4, and 5 because these were present on the right hand side of the perpendicular line, with E1 being the most favourable and E3 and 6 being the least favourable environment.

Since, the IPCA 2 scores explain a considerable portion of the GEI (12.492%), the IPCA1 scores were plotted against the IPCA2 values to further investigate adaptation (Fig. 2). The IPCA scores of genotypes in the AMMI study indicate environmental stability or adaptation (Gauch and Zobel, 1996). The higher the genotype's IPCA score, the better it is suited to specific environments (Admassu *et al.,* 2008). The genotype is more stable or adaptable across all environments sampled if the IPCA values are close to zero. The best suited hybrids to most environments were H9 and 17 (Ajeet and Swaraj-1516), with IPCA scores near to zero, showing their stability across all environments, according to a biplot of the first two IPCA. Among the environments tested in this study, only E2 noted IPCA 1 score near to zero line. The IPCA 2 scores for environments were far from zero. This suggests that all of the environments have a high GEI potential.

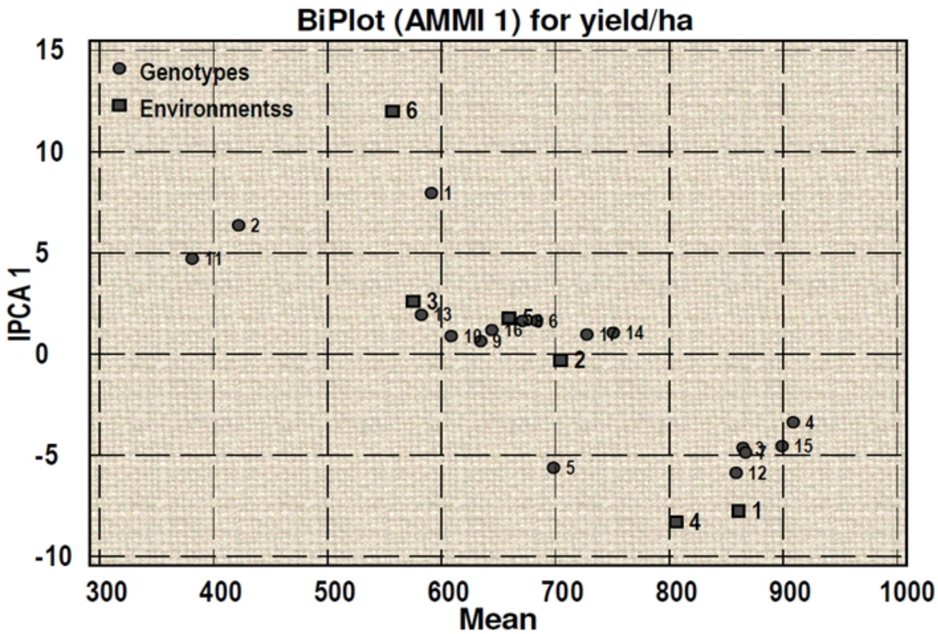

Fig. 1. Biplot of interaction principal component analysis (PCA) axis 1 and mean yield/ha (q).

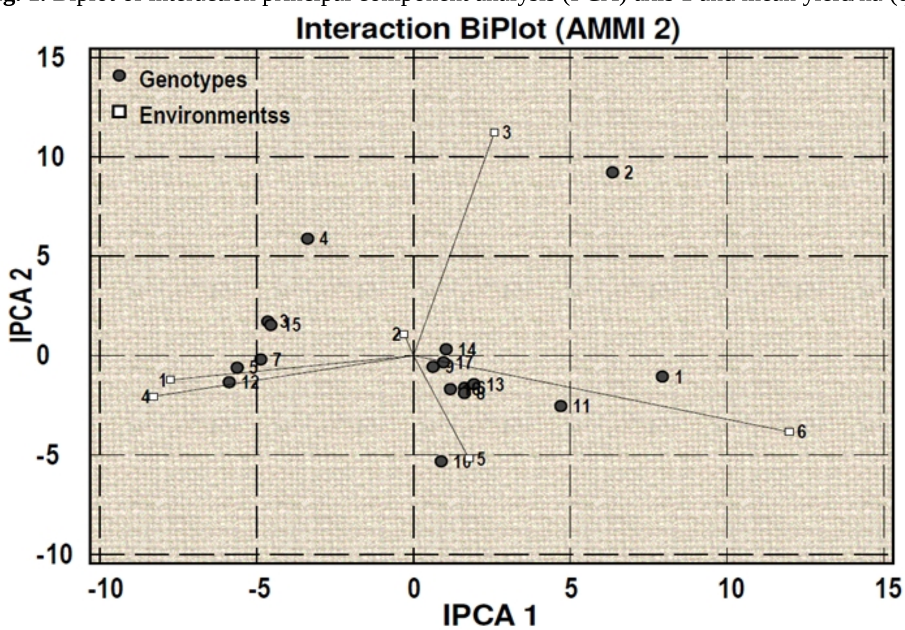

Fig. 2. (PCA) axis 1 versus axis 2 for 17 hybrids of tomato grown in 6 environments.

CONCLUSION

The AMMI analysis model for tomato fruit yield found significant variation for main and interaction factors, showing that there is a lot of variation between hybrids, locations, years, and their interactions. For the plant breeder, the presence of strong G×E interaction in hybrids can be both an opportunity and a challenge. Using 54 degrees of freedom, three significant IPCAs were recovered from the interaction component in this investigation, which accounted for 98.139 percent of the total GEI SS. H3 and 7 (Shalimar tomato hybrid-1, PS-255) were the most stable and provide the highest yields, whereas H4 and H12 (Shalimar tomato hybrid-2, Bhaskar Improved) were less stable but provide the highest yields. Among the hybrids, H9 and 17 (Ajeet and Swaraj-1516) were the best suited hybrids to most environments, with IPCA values near to zero, showing their stability across all environments. Further, these hybrids can be evaluated in more environments to assess their performance and adaptability and possible recommendations to the farming community.

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How to cite this article: Ummyiah, H.M., Zeenat Fayaz, Baseerat A., Shehnaz M., M. Mudasir Magray and Gazala, N. (2021). Genotype x Environment Interaction and Fruit Yield Stability in Tomato Hybrids under Kashmir Valley conditions using Additive Main Effects and Multiplicative Interaction (AMMI) Model. *Biological Forum – An International Journal*, *13*(3): 249-254.