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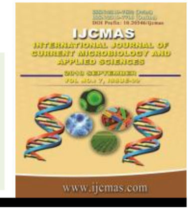

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Yield Stability of Chilli (*Capsicum annuum* L.) Hybrids Differing for Fruiting Habit Traits

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ABSTRACT

Keywords

AMMI stability, Fruiting habit, GGE bi-plot, Fresh fruit yield, Chilli

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For most quantitative traits in crop plants, genotype × environment interaction (GEI) is the rule rather than the exception. The best approach to cope with GEI is to exploit it by identifying genotypes best suited to specific environments so that the productivity in given environment is maximized. Fruit yield stability of 14 single cross hybrids of chilli across two seasons (summer and rainy seasons) over two years (2016 and 2017) was determined using AMMI and GGE bi-plots models at the Department of Genetics and Plant Breeding (GPB), Gandhi Krushi Vignana Kendra (GKVK), Bengaluru in randomized block design with two replications. Data were recorded on randomly chosen ten plants for fruits plant^{-1} and fresh fruit yield plant^{-1} and used to estimate AMMI stability value (ASV) and stability index (SI). GGE bi-plots were used as visual criteria for assessment of stability of hybrids. The results indicated that influence environments on the performance of hybrids for fresh fruit yield plant^{-1} and fruits plant^{-1} was greater than main effects of hybrids and hybrid × environment interaction. The hybrids, PC1 × CMS 6B and JL × PC1 were found to stable across seasons and expressed high mean performance for fresh fruit yield plant^{-1} and fruits plant^{-1}, respectively. It is also evident that hybrids bearing single and pendant fruits were more often widely adapted than those bearing other types of fruiting habit.

Introduction

Chilli (*Capsicum annuum* L.) is one of the most important vegetable-cum-commercial crops. Chilli is highly sensitive to environmental variations and shows large yield fluctuations. Differential performance of chilli genotypes across environments represented by temporal and spatial variations is one of the factors that retards breeding for performance stability and wide adaptation. The best approach to cope with genotype × environment interaction is to exploit it by identifying genotypes best suited to specific environments so that the productivity in a given environment is maximized. In this context, the present study was conducted to determine the fruit yield stability of chilli single cross hybrids across two seasons over two years using AMMI (Gauch and Zobel, 1988) and GGE bi-plots models(Yan *et al.*, 2000).

Materials and Methods

Basis genetic material

The basic genetic material consisted of genotypes differing in fruit bearing traits namely, fruits node^{-1} [single (S) and cluster (C)] and fruit orientation [erect (E) and pendant (P)] (Table 1). Fourteen F_1 hybrids were generated using nine parental genotypes indifferent types of crosses (CE × SE, CP × SP, SE × CP, CE × SP, CE × CP, SE × SP and CP × SE) in the polyhouse during 2015 rainy season.

Evaluation of hybrids

Fourteen hybrids were evaluated at the experimental plots of department of Genetics and Plant Breeding (GPB), Gandhi Krushi Vignana Kendra (GKVK), Bengaluru in randomized block design with two replications across four seasons (*Summer*-2016, *Kharif*-2016, *Summer*-2017 and *kharif*-2017). Forty days old seedlings of all fourteen hybrids were planted during 2016 and 2017 *summer* and rainy seasons by maintaining a spacing of 0.75m between rows and 0.4m between plants within row.

The recommended crop management practices were followed during the crop growth period to raise the healthy crop. Data were recorded on randomly chosen ten plants for fruits plant^{-1} and fresh fruit yield plant^{-1}.

Statistical analysis

The replicate mean fruits plant^{-1} and fresh fruit yield plant^{-1} of 14 hybrids were subjected to statistical analysis following Additive Main effects and Multiplicative Interaction (AMMI) model (Gauch and Zobel, 1988) to detect and characterize the patterns of interaction of hybrids with environments represented by four seasons. The additive main effects of hybrids and seasons were fitted by univariate ANOVA followed by fitting hybrid × season interaction by principal component (PC) analysis based on the following AMMI II model.

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

Where, Y_{ij} is the trait value of ith hybrid in the jth season, μ is the experimental mean trait value, gi and e_j are the ith hybrid and jth season mean deviation from experimental mean trait value respectively. λ_k is the square root of Eigen value of the kth IPC axis, α_{ik} and γ_{jk} are the interaction IPC scores for kth IPC of the ith hybrid and jth season, respectively and ε_{ij} is the residual.

The parameters of AMMI II model were estimated using least square principle implemented by GENSTAT software, version 15.

Criteria for interpretation of hybrid × season interaction patterns and hybrid stability

Visual and objective criteria were used to interpret GEI patterns of yield traits of hybrids and their stability. *Visual criteria for assessment of stability of hybrids*: This was based on Genotype (hybrid) + Genotype (hybrid) × environment (season) (GGE) biplot (Yan *et al.*, 2000). The GGL biplot is based on the following model.

$$Y_{ij}-\overline{Y_{ij}}=\lambda_1\alpha_{i1}\gamma_{j1}+\lambda_2\alpha_{i2}\gamma_{j2}+\varepsilon_{ij}$$

Where, Y_{ij}= trait mean of jth hybrid in the jth season; Y_j= trait mean of all the hybrids in the jth season; λ_1 and λ_2 are the square root of Eigen values of first and second IPC axes, respectively; α_{i1} and α_{i2} are the scores of the first and second IPC, respectively for the ith hybrid, γ_{i1} and γ_{i2} are the first and second IPCs respectively for jth season.

Objective criteria for assessment of stability of hybrids

AMMI stability value (ASV) (Purchase *et al.*, 2000) and stability index (SI) (Farshadfar, 2011) were used to determine stability of each hybrid.

$$ASV = \sqrt{\left[\frac{SSIPC1}{SSIPC2}(IPC1\ score)\right]^2 + (IPC2\ score)^2}$$

Where, SSIPC1 and SSIPC2 are sum of squares attributable to first two IPC's. Greater ASV indicates the higher stability of hybrid across seasons (Purchase, 2000).

To facilitate simultaneous selection of hybrid for high yield and stability, stability index (SI) which incorporates both yield and stability in a single criterion (Farshadfar, 2011) was estimated as SI= RASV+RY (*i.e.*, rank of hybrid based on ASV added to rank of hybrid based on trait mean over seasons).

Results and Discussion

The hybrids differed and interacted significantly across seasons (Table 2). Capture of more than 95 *per cent* of the hybrid × season interaction variability by IPCA 1 and IPCA 2 suggested the adequacy of the AMMI II model.

Several authors reported and attributed most of the G×E interaction sum squares to first two IPCA axes (Crossa *et al.*, 1990; Purchase, *et al.*, 2000).

Based on the ASV score, the hybrids PJ × CMS 10B, PC1 ×CMS 10B and JL × CMS 10B were found most stable for fresh fruit yield plant^{-1}, as indicated by low magnitude of ASV, the hybrids UA × PJ, PS × CMS 6B and PJ × CMS 10B were found most stable for fruits plant^{-1} as indicated by low ASV score (Table 3). Based on SI the hybrids PC1 × CMS 6B, PJ × GB and PS × PC1 for fresh fruit yield plant^{-1}and JL × PC1, JL × UA and JL × CMS 10B were found stable for fruits plant^{-1} (Table 3).

Most of these best three stable and high yielding hybrids bore single and pendant fruits.

Genotype and Genotype by Environment interaction (GGE) bi-plot analysis

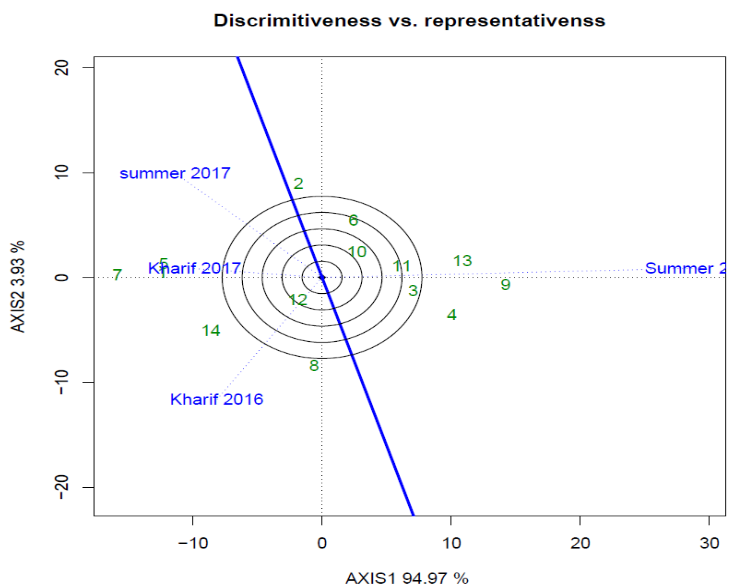
Discriminating ability and representativeness of locations

Assessment of discriminating and representativeness of test seasons is based on the length of season's vectors, and the angle between the test season vectors and average season coordination (ASG) in the GGE bi-plot. The lines that connect the test season points to the origin of GGE bi-plot is referred to as season vectors. A single-arrowed line (ray) passing through the origin of the bi-plot and the average of the seasonis referred as ASC. The average season is represented by the small circle at the end of the arrow (Yan and Tinker, 2006). Shorter the season vectors, lower is the discriminating ability of the season; longer the vector, higher is the discriminating ability of the season. A test season that has a smaller angle with ASC is more representative of test season.

The cosine of the angle between the vectors of two seasons approximates the correlation between them. While acute angle between the vectors of test season indicate positive correlation or similarity between them, obtuse and right angles indicate negative correlation or dissimilarity, and no relationship respectively between the test seasons.

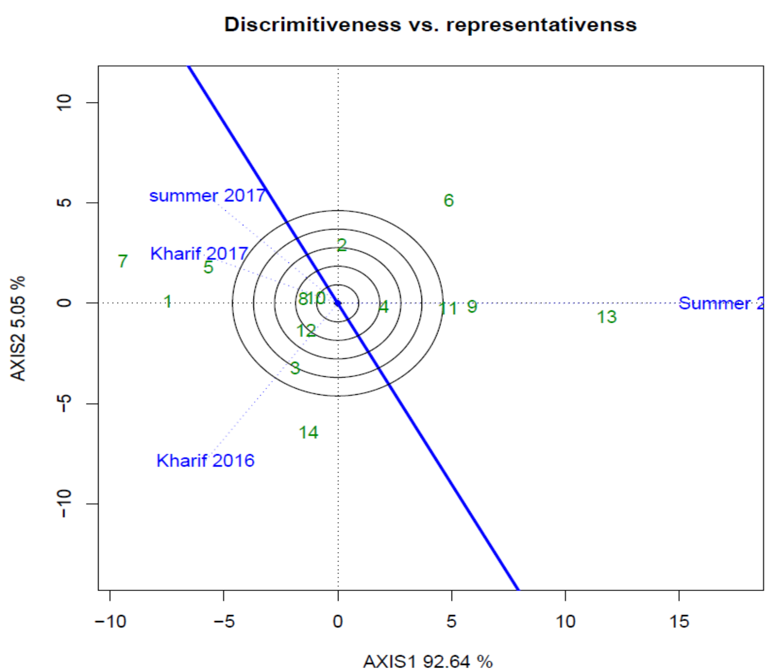
In the present study, environment represented by *summer*-2016 discriminated the hybrids better than those represented by *kharif*-2016, *summer*-2017 and *kharif*-2017 as indicated by their shorter vector length. The acute angle between the vectors of *kharif*-2016 and *kharif*-2017, and *kharif*-2017 and *summer*-2017 indicated their similarity of effects on hybrid expression. The obtuse angle between *summer*-2016 and other three environments indicated their dissimilarity. The close/acute angle of the *kharif*-2016 vector with ASC suggested better representativeness of *kharif*-2016 than other seasons (Fig. 1a and 1b).

Fig.1a Discriminative vs. representativeness view of GGE bi-plot for fresh fruit yield plant^{-1}



Legend	
1	JL × UA
2	JL × PC1
3	PJ × PC1
4	UA × PJ
5	PC1 × CMS10B
6	JL × CMS10B
7	JL × CMS8B
8	PJ × CMS10B
9	PJ × GB
10	PC1 × CMS6B
11	JL × PJ
12	PS × CMS6B
13	PS × PJ
14	PS × PC1

Fig.1b Discriminative vs. representativeness view of GGE bi-plot for fruits plant^{-1}



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10	PC1 × CMS6B
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12	PS × CMS6B
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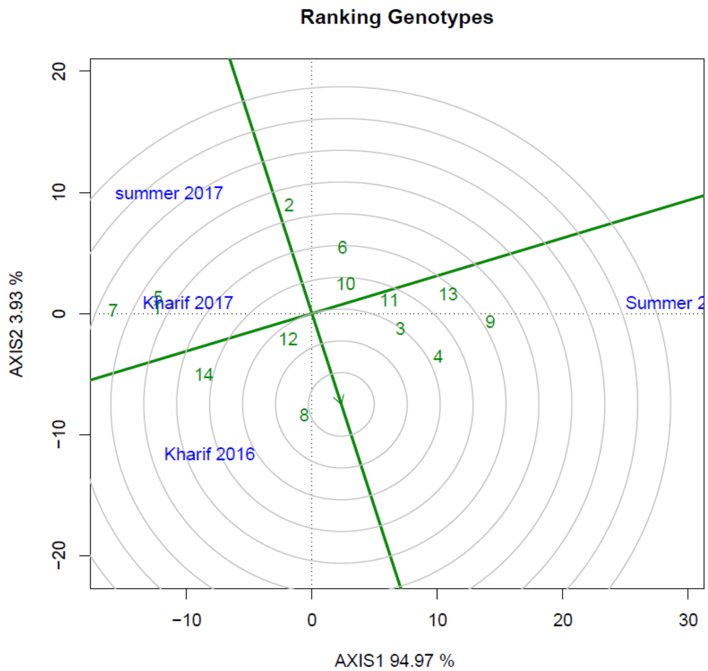
14	PS × PC1

Fig.2a Average environment coordination (AEC) view of GGE bi-plot based on genotype-focused scaling for comparison of genotypes with the ideal genotype for fresh fruit yield plant^{-1}



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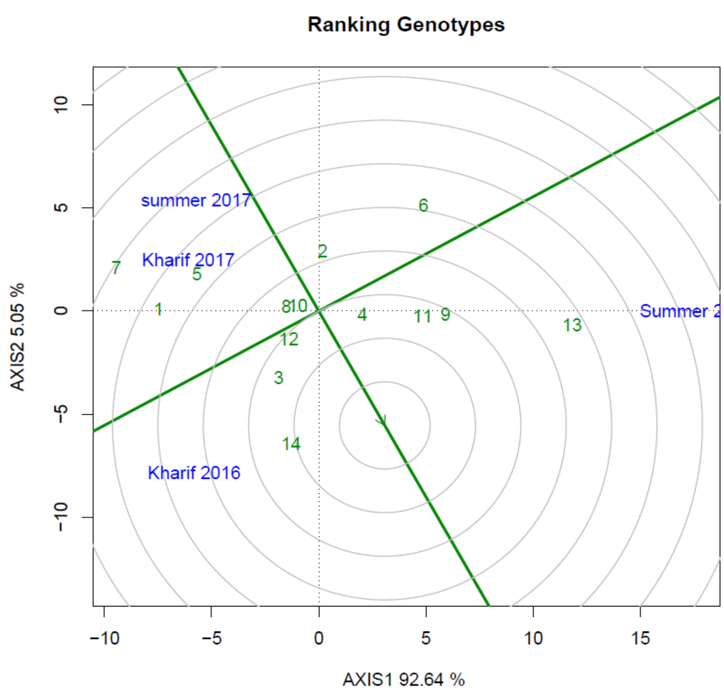

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Fig.3a Average environment coordination (AEC) view of GGE bi-plot based on environment-focused scaling for the mean performance *vs*. stability for fresh fruit yield plant^{-1}

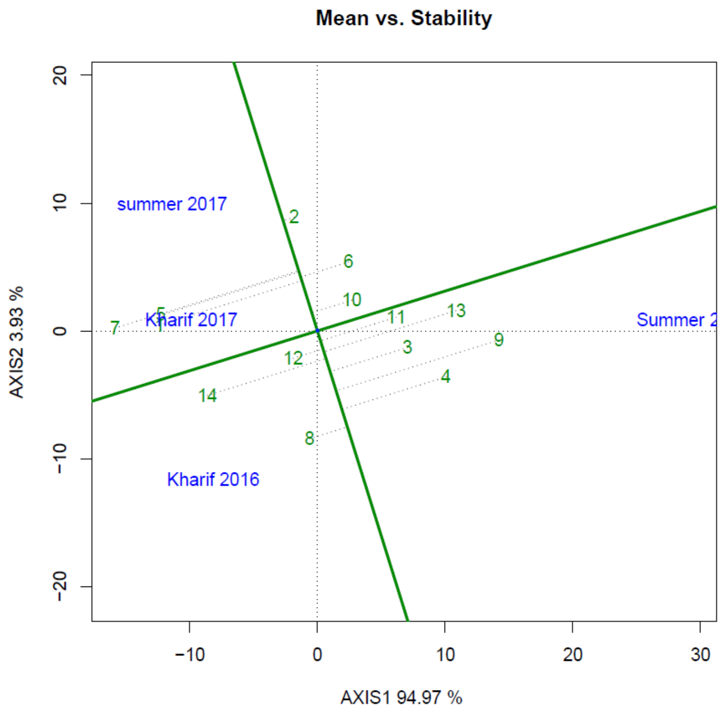

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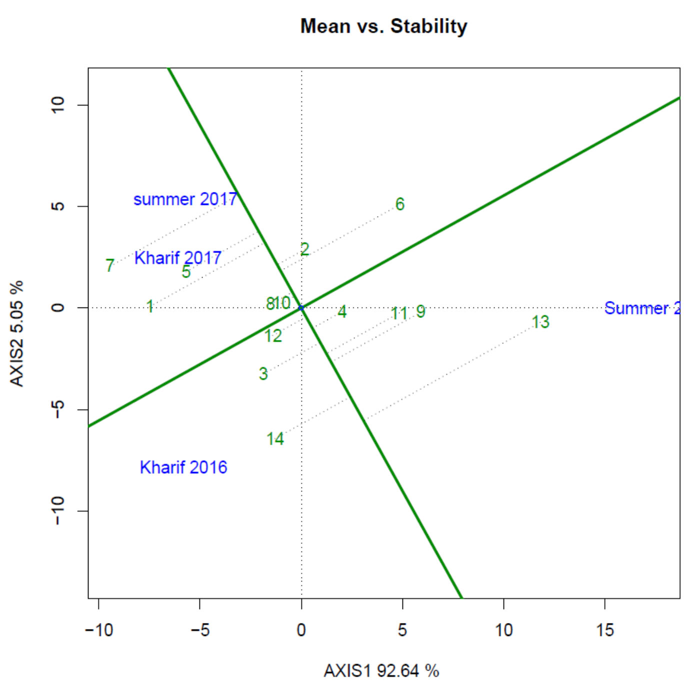
Fig.3b Average environment coordination (AEC) view of GGE bi-plot based on environment-focused scaling for the mean performance *vs*. stability for fruits plant^{-1}



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9	PJ × GB
10	PC1 × CMS6B
11	JL × PJ
12	PS × CMS6B
13	PS × PJ
14	PS × PC1

Fig.4a Polygon view of GGE bi-plot based on the symmetrical scaling for 'which-won-where' pattern of genotypes and environments for fresh fruit yield plant^{-1}

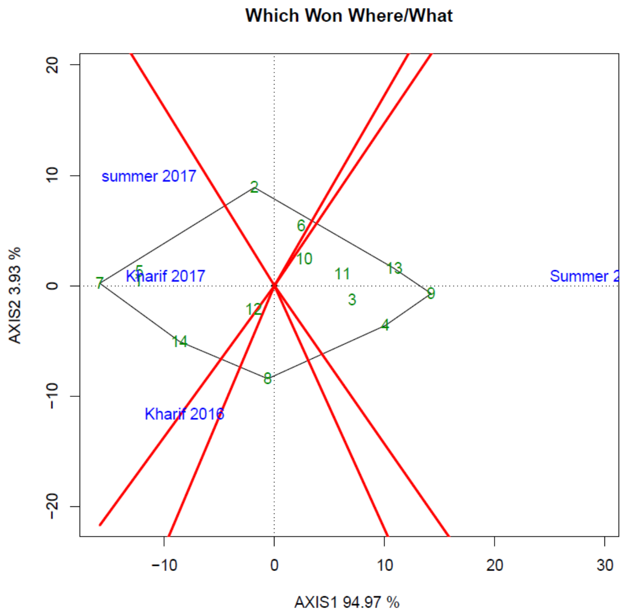

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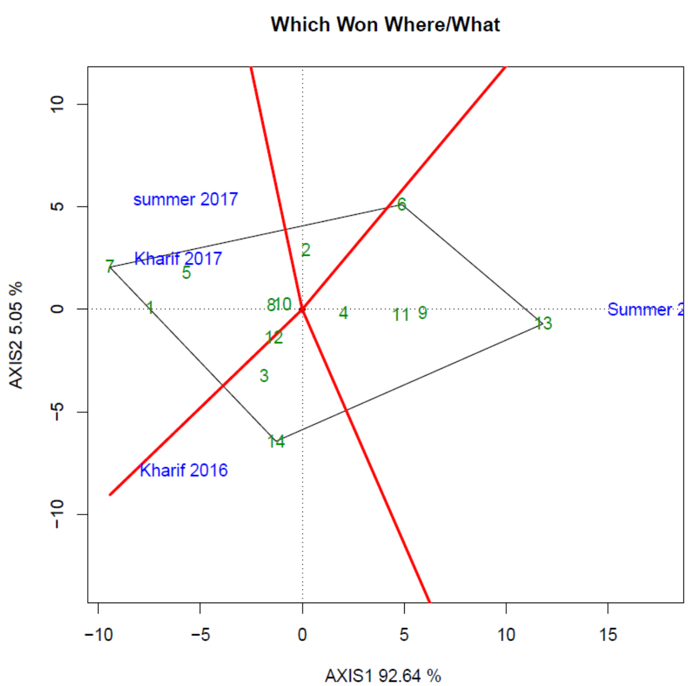
Fig.4b Polygon view of GGE bi-plot based on the symmetrical scaling for 'which-won-where' pattern of genotypes and environments for fruits plant^{-1}



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9	PJ × GB
10	PC1 × CMS6B
11	JL × PJ
12	PS × CMS6B
13	PS × PJ
14	PS × PC1

Table.1 Salient features of genotypes used in the study

Genotypes	Source	Characteristics
CMS 8B	AVRDC, TAIWAN	Corresponding maintainer line of CMS 8A, fruits are short, single pendant fruiting habit, tall stature, good yielder.
CMS 10B	AVRDC, TAIWAN	Corresponding maintainer line of CMS 10A,fruits are medium length, single pendant fruiting habit, short stature, medium yielder
Phulejyothi (PJ)	MPKV, Rahuri	Plants are tall, fruits are medium length, cluster pendant fruiting habit.
Pusasadabahar (PS)	IARI, New Delhi	Plants are medium statured, fruits are short, clustered erect fruiting habit.
Japanese long (JL)	IARI, New Delhi	Selection from Pusasadabahar, plants are tall, fruits are medium length, clustered erect fruiting habit.
Pant C-1(PC1)	GB Pant Agricultural University (UP)	Medium tall, fruits are very short, single erect fruiting habit, light green to red, highly pungent, susceptible to thrips and mites, good yielder.
Gowribidanur (GB)	Collection - Gowribidanur	Very tall, fruits are very short with thick shoulder, single pendant fruiting habit, light green to red, highly pungent, susceptible to thrips and mites, medium yielder.
Utkal Awa (UA)	OUAT, Bhubaneshvar	Dwarf, fruits are short and thick, single erect fruiting, dark green to red, highly pungent, susceptible to thrips and mites, good yielder.
CMS 6B	AVRDC, TAIWAN	Corresponding maintainer line of CMS 6A, Fruits are long and thick, single pendant fruiting, short stature, good yielder

Table.2 Combined AMMI analysis of variance over four seasons

Source	Degrees of freedom	Fruits plant^{-1}	% variation	Fresh fruit yield plant^{-1}	% variation
Hybrids	13	10592**	6.85	76769**	6.18
Seasons	03	476234**	71.11	3949415**	73.46
Hybrids × season	39	9498**	18.43	72473**	17.52
IPCA 1	15	22877**	92.63	178950**	94.97
IPCA 2	13	1438	5.05	8554	3.93
Residual	11	780	2.32	2817	1.1
Error	52	1365		7859	

*=Significant at P=0.05 and **=Significant at P=0.01

Table.3 Estimates of AMMI stability value (ASV) and stability index (SI) of 14 hybrids evaluated across four seasons

Hybrids	Cross type	Fruits plant^{-1}					Fresh fruit yield plant^{-1}				
		Mean	ASV score	Rank based on ASV	SI score	Rank based on SI	Mean	ASV score	Rank based on ASV	SI score	Rank based on SI
JL × UA	CE × SE	116.50	34.49	06	23	02	366.8	170.07	07	04	14
JL ×PC1	CE × SE	163.50	173.44	13	26	01	479.1	382.55	14	10	11
PJ × PC1	CP × SE	143.90	37.45	07	04	14	532.1	64.83	05	15	08
UA × PJ	SE × CP	116.50	4.36	01	10	12	549.1	46.11	03	20	04
PC1 ×CMS10B	SE × SP	205.90	25.97	04	18	04	337.2	44.81	02	08	13
JL ×CMS10B	CE × SP	164.80	108.61	11	23	03	535.1	148.64	06	20	05
JL ×CMS8B	CE × SP	208.30	216.90	14	18	05	315.6	298.44	12	09	12
PJ ×CMS10B	CP × SP	211.30	24.56	03	12	09	484.0	16.89	01	11	09
PJ × GB	CP × SP	163.70	27.78	05	12	10	663.4	208.16	08	22	02
PC1 ×CMS6B	SE × SP	146.20	104.51	10	16	06	446.6	58.92	04	24	01
JL × PJ	CE × CP	147.80	89.96	09	14	07	558.2	261.49	10	17	07
PS ×CMS6B	CE × SP	181.20	17.95	02	13	08	423.9	296.51	11	18	06
PS × PJ	CE × CP	185.60	88.95	08	09	13	510.1	343.26	13	11	10
PS × PC1	CE × SE	92.10	137.36	12	12	11	377.6	243.34	09	21	03

Ranking hybrids relative to ideal hybrid

An ideal hybrid should have both high mean performance and high stability across seasons. An ideal hybrid (center of concentric circles) is the point on ASC (wide adaptation) in the GGE bi-plot in the positive direction and has a vector length equal to the longest vector of the hybrid on the positive side of ASC. Using the ideal hybrid as the center, concentric circles are drawn to help visualize the distance between each hybrid and ideal hybrid. The hybrid located closer to the "ideal hybrid" is more desirable than others.

In the present study, the hybrids PJ × CMS 10B closely followed by PS × CMS6B and PJ × PC1 were adjudged as ideal ones as indicated by their location within the inner most concentric circle for fresh fruit yield plant^{-1}. Similarly, the hybrids PS × PC1, PJ × PC1 and UA × PJ were found ideal ones for fruits plant^{-1} (Fig. 2a and 2b). All these ideal hybrids bore single fruits node^{-1}.

Mean performance vs. adaptability patterns view of GGL bi-plot

The mean performance and adaptability could be visualized through location of hybrids in relation to ASC view of GGE bi-plot based on season-focused scaling for the mean performance and stability of hybrids. The single arrowed ASC points to higher mean performance of the hybrids across seasons (Yan, 2001). The hybrids with their points located towards arrow of ASC are considered to exhibit high mean performance. On the contrary, the hybrids with their points located opposite ASC arrow are considered to exhibit lower performance. Further, the relative lengths of projections of the hybrids from ASC are indicative of their relative adaptability. The greater the absolute length of the projections of hybrids, greater would be their poor adaptability (Yan and Kang 2002).

In the present study, short projections of hybrids PJ ×CMS10B, PS × CMS 6B and PC1 × CMS 6B than others indicated their wide adaptation for fresh fruit yield plant^{-1}.All these hybrids bore single and pendant fruits. The hybrids, PS × PC1 and PS × PJ were found relatively closer to ASC than other hybrids and hybrid PS × PJ had greater projection length indicating high performance but poor adaptability for fruits plant^{-1}. These hybrids bore pendant fruits (Fig. 3a and 3b).

Which–won–where pattern

One of the features of GGE bi-plot is its ability to show which – won – where pattern of a genotype. This feature is shown by polygon view of the GGE bi-plot. A polygon is drawn on hybrids that are farthest from the bi-plot origin so that all other hybrids fall within the polygon. The perpendicular lines starting from GGE bi-plot origin are drawn to each side of the polygon. The perpendicular lines are equality lines between adjacent hybrids on the polygon. The hybrids located on the vertices of the polygon perform either the best or poorest in one or more seasons (Yan *et al.,* 2000). The equality lines divide the bi-plot into sectors. The vertex hybrids in each sector are the winning hybrids at seasons whose markers (point) fall into the respective sector (Yan *et al.,* 2000). Seasons within the same sector share the same winning hybrids, and seasons in different sectors have different winning hybrids, thus polygon view of a GGE bi-plot indicates presence or absence of cross-over GEI (Yan and Rajcan, 2002).

The patterns of adaptability of the hybrids were investigated graphically following GGE bi-plot. The hybrids JL × PC1, UA × PJ, JL ×CMS8B, PJ ×CMS10B, PJ × GB, PS × PJ and PS × PC1positioned at the vertices of the polygon of GGE bi-plot. The hybrids PC1 × CMS10B and JL × CMS8B were found suitable to *kharif*-2017 season; PJ × CMS10B to *kharif*-2016 season and hybrid JL × PC1 to *summer*-2017 season for fresh fruit yield plnat^{-1}.

Hybrids PC1 ×CMS10B and JL ×CMS8B were found suitable to *Kharif*-2017 and *Summer*-2017 seasons and the hybrid PS × PC1 to *Kharif*-2016 seasons as indicated by their locations at their respective vertices for fruits plant^{-1} (Fig. 4a and 4b).

The results of the study indicated that the environments represented by four seasons exerted greater influence on the performance of hybrids for fresh fruit yield plant^{-1} and fruits plant^{-1}than main effects of hybrids and hybrid × environment interaction. The hybrids PC1 × CMS 6B and JL × PC1 were found to stable across seasons and expressed high mean performance for fresh fruit yield plant^{-1} and fruits plant^{-1}, respectively. It is also evident that hybrids bearing single and pendant fruits were more often widely adapted than those bearing other types of fruiting habit.

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