ADDITIVE MAIN EFFECTS AND MULTIPLICATIVE INTERACTION FOR SEED COTTON YIELD PERFORMANCE AND STABILITY IN *BT* COTTON HYBRIDS (MON531 AND MON15985)

ABSTRACT

A study was conducted to understand the stability of seed cotton yield of 105 *Bt* cotton hybrids (BGI and BGII) using Additive Main effects and Multiplicative Interactions (AMMI) analysis across three diverse locations in India during rainy season 2018. This study holds importance as the hybrids were resistant to *Helicoverpa* bollworms due to *Bt* events (MON531 and MON15985) in them which were expected to nullify variation arising out of differential bollworm pressure in different location, unlike in non *Bt* hybrids where this variation also played role in the stability of the hybrids. The main effect differences among hybrids (41.23 %), environments (39.56 %) and the interaction effects (19.21%) were highly significant of the total variance of seed cotton yield indicating a large difference between the testing location causing different hybrids to perform differently across the testing environments. The first two principal components axes (IPCA I and IPCA II) were highly significant and contributed 52.12 % and 47.88% of total interaction respectively. The distance from the origin and the placement of locations in different quadrants of biplot reflected that the locations were substantially discriminatory as Aurangabad and Dharwad, which were high yielding and Raichur was low yielding. Results showed that hybrids IAHH-8096 BGII, IAHH-8103 BGI, IAHH-8061 BGII and IAHH-8007 BGII were having lowest interaction and stable across the location, whereas hybrids IAHH-8080 BGI, IAHH-8084 BGI, IAHH-8004 BGII and IAHH-8105 BGI were having more interaction and unstable genotypes. Large frequency of hybrids (57) were stable with IPCA scores nearing zero and low ASV values which is attributed resistance to bollworm due to *Bt* events.

Keywords: Bt cotton, Stability, Genotype × Environment Interaction, Multiplicative model

1. INTRODUCTION

Cotton is an important leading natural fiber and gives 90% employment in the textile industry. Bollworm-resistant cotton is popularly known as *Bt* cotton (MON531 and MON15985) has been the most preferred technology in the major cotton growing countries in the world. Globally transgenic *Bt* cotton is grown under 18.4 million hectares in fifteen countries [1]. The reason for the introduction of *Bt* cotton in India was to counter insect pests - Bollworm complex that includes, American (*Helicoverpa armigera*), *and pink bollworm (Pectinophora gossipiyella* and tobacco budworm (*Heliothis virescens*) which used to cause significant damage to the crop, resulting in low productivity. Consequently, Mahyco (Maharashtra Hybrid Seed Company), in collaboration with Monsanto, introduced *Bt* cotton technology into India in 2002. *Bt* cotton carries the *Cry1Ac* gene (MON531 event- BGI) derivative from the common soil bacterium *Bacillus thuringiensis* var. *kurstaki*, which results in the expression of the endotoxin crystal (*Cry1Ac*) protein that confers resistance to the bollworm complex [2]. Cotton event 15985 (BG II) is proposed to protect the cotton from feeding by a range of Lepidopteran species including tobacco budworm (*Heliothis virescens*), pink bollworm (*Pectinophora gossypiella*), cotton bollworm (*Helicoverpa zea*), cabbage looper (*Trichoplusia ni*), saltmarsh caterpillar (*Estigmene acrea*), cotton leaf perforator (*Bucculatrix thurbeiella*), soybean looper (*Pseudoplusia includens*), beet armyworm (*Spodoptera exigua*), fall armyworm (*Spodoptera frugiperda*), yellow-striped armyworm (*Spodoptera ornithogolli*) and European corn borer (*Ostrinia nubilalis*) which was permitted for cultivation in 2006 in India [3]. In India, *Bt* cotton cultivar forms can be classified as *Bt* lines/varieties and hybrids derived crossing two cotton lines. In India, 95% of the cotton area is covered by *Bt* cotton hybrids. The development of genetically stable *Bt* cotton cultivars has been a priority for cotton breeding. Commercial seed companies are aiming at the development of hybrids with high yield and wider adaptability in such cases, effective multi-environment testing (MET) and better handling of data assumes significant importance to select best performing hybrids across diverse environments. In the cotton-growing area major is covered by rainfed, marginal soils. For lint yield and lint, quality is mainly dependent on the growing condition. A selection of adaptable and stable hybrids across the environment is a crucial part of plant breeder as it interacts with environments very different from place to place. Phenotypes respond to genotypes differently according to different environmental factors is defined as G×E. The concept of genotype-environment interactions leads to measuring the agronomic stability of the genotype and under the biological concept stable genotype is one, whose phenotype shows little deviation from the expected character level when the performance of the genotype is tested over several environments [4]. Seed cotton yield stability is influenced by the capacity of a genotype to react to environmental conditions, which is determined by the genotype's genetic composition. The adaptability and stability of a genotype are useful parameters for recommending cultivars for known cropping conditions [5 and 6].

Scientists have used different statistical tools to find the nature of genotypic interactions with the environments. Among these statistical techniques, additive main effects and multiplicative interaction (AMMI) is widely used. For the accurate analysis of METs, the AMMI model is a valuable tool due to the accuracy that it provides in GE interaction studies [7 and 8]. AMMI analysis combines the additive parameters of traditional ANOVA with multiplicative parameters of PCA (principal component analysis). Most of the studies on the stability of cotton hybrids have been conducted using non-*Bt* cotton, however, this study was using newly developed *Bt* cotton hybrids that were resistant to bollworms. Differential bollworm pressure in different locations was also a major contributor to the variation in the performance of hybrids, but with *Bt* cotton that is mostly nullified. It is interesting to see the AMMI stability analysis results through this prism too in addition to the contribution of the genetic backgrounds for genotypic stability.

2. MATERIAL AND METHODS

2.1 Plant material

The experiments were conducted during 2018 rainy season with a set of 105 hybrids comprising of 69 BG II (MON15985), 34 BG I (MON531) and two non-*Bt* hybrids. These 105 test hybrids were compared with two each of BG II, a non-*Bt* hybrid and a non- *Bt* variety as commercial controls. The replicated randomised block design trials were conducted in three diverse commercial locations of Indo- American Hybrid Seeds, Research and Development centres situated at

Dharwad and Raichur in Karnataka and Aurangabad in Maharashtra of India. Details of the diverse environments are given in Table 1. The plot size was maintained by two rows of 9 m length of 10 dibbles spacing of 90 cm row to row and 90 cm between plant to plant. Observations on seed cotton yield kg/plot in all the replications were measured which was later converted into kg/ha.

Table 1. Geographical coordinates, weather status, soil and climatic details of three locations

Location	Coordinates	Coppen climate classification	Elevation (m)	Soil	Rainfall (mm) during cotton growing season
Aurangabad	*19.88°N 75.32°E*	Semi-Arid (Bsh)	568	Deep black soil	961.48
Dharwad	15^o 26'N 75^o07' E	Tropical wet and dry climate (Aw)	741	Medium black	648.4
Raichur	16.2°N 77.37°E	Semi-arid to dry (Bsh)	407	Medium black soil	696.2

2.2 Statistical analysis

In the multiplicative stability model, AMMI analysis includes ANOVA and PCA in a unified approach that can be used to analyze multiple yield trials [7 and 8]. The AMMI analyses were performed using GEA-R (Genotype by Environment Analysis with R) [9]. The AMMI uses ANOVA to test the main effects of genotypes and environments and PCA to analyze the residual multiplicative interaction between genotypes and environments to determine the sum of squares of the G × E interaction, with a minimum number of degrees of freedom. Since AMMI does not provide a quantitative measurement, it is necessary to quantify and rank genotypes based on their yield. AMMI Stability Value (ASV), length of genotype and environment markers of the origin in a two-dimensional plot of IPCA I sores against IPCA II scores were calculated according to Purchase *et al.* [10]. Yield Stability Index (YSI) incorporates both mean yield and stability in a single criterion. The minimum values of YSI desirable genotypes with high mean yield and stability.

3. RESULTS AND DISCUSSION

3.1. Analysis of variance by AMMI analysis

Analysis of variance of AMMI model was highly significant for genotype, environment and Genotype × Environment Interaction (GEI) effects (p=0.05) for seed cotton yield (Table 2) indicating differences between testing locations and also between the *Bt* cotton hybrids. The Sum of squares of genotype (41%) and environment (39.6%) were almost double compared to GEI variance (19%) indicating that most of the genotypes were diverse and stable across the location (irrespective of seed cotton yield) and environments were diverse. The genotype × environment interaction (GEI) sum of squares using principal component analysis revealed that the first and second principal components (IPCA I and IPCA II) were highly significant and explained 52.12 % and 47.88% respectively [16]. The average seed cotton yield of the hybrids ranged from 1646 kg/ha (IAHH-8093 BGII) to 4095 kg/ha (IAHH-8039 BGI). The interaction between genotypes and environments was more predominant in total phenotypic variability than the variety and environmental influence by itself [11,12, 13, 14]. So, a cotton hybrid must show good performance in a wide range of environmental conditions [15]. Significance of mean squares due to genotypes, environments and their interaction revealed higher genetic diversity among cotton genotypes because of their diverse genetic makeup and variable environments where the genotypes were grown. The significance in environments, genotypes and their interaction for various yield and morphological traits in cotton has been obtained in the findings of Machado *et al.* [16]. In various environments, the genotypes perform differently and reveal significant GEI in upland cotton. Among 105 hybrids, 22 BGI and 30 BGII hybrids were out yielded grand mean (2787 kg/ha) from across the location (Table 3). Such outyielded BGI hybrids seed cotton yield ranged from 2838 kg/ha to 4095 kg/ha with a mean of 3301 kg/ha. Likewise, BGII hybrids ranged from 2821 kg/ha to 3622 kg/ha with a mean of 3091 kg/ha [17 and 18]. But none of non- *Bt* hybrids were not out yielded over transgenic hybrids.

Table 2. Analysis of variance of main effects and interactions (AMMI) for seed cotton yield in hybrids

Source of Variation	df	SS	MS	Variability explained (%)	Cumulative variability (%)
Environment	2	140068421.30	70034210.65**	39.56	39.56
Genotypes (G)	108	145996724.50	1351821.52**	41.23	80.79
G X E Interaction	216	68040621.90	315002.88**	19.21	100.00
IPCA 1	109	35462977.35	325348.42**	52.12	52.12
IPCA 2	107	32577644.54	304463.97**	47.88	100.00
Residuals	326	14534339.16	44447.52	0	0

Table 3. Mean performance and AMMI stability estimates for the cotton hybrids from across locations.

Sl no	Hybrids	SCY (kg/ha)	AMMI Stability estimates					
			IPCA 1	IPCA 2	ASV	Rank ASV	YSI	Rank YSI
1	IAHH-8001BG II	3146	-3.05	-1.99	3.76	25	48	23
2	IAHH-8002BG II	2459	-6.36	-0.35	6.64	49	136	87
3	IAHH-8003BG II	2644	2.04	0.21	2.14	12	79	67
4	IAHH-8004BG II	3380	-14.67	3.52	15.71	105	119	14
5	IAHH-8005BG II	3622	-5.38	8.99	10.6	77	82	5
6	IAHH-8006BG II	3225	-2.38	-2.67	3.65	23	41	18
7	IAHH-8007BG II	3174	-1.98	-1.51	2.56	15	36	21
8	IAHH-8008BG I	2643	1.86	-6.83	7.1	55	124	69
9	IAHH-8009BG II	2009	-2.3	-8.4	8.73	69	173	104
10	IAHH-8010BG I	2601	4.34	-4.14	6.14	43	118	75
11	IAHH-8011BG I	2610	3.73	4.58	6.01	42	116	74
12	IAHH-8012BG I	2643	2.92	0.35	3.07	19	87	68
13	IAHH-8013BG I	2692	-0.88	1.09	1.43	7	71	64
14	IAHH-8014BG I	2565	-1.55	-5	5.26	34	113	79
15	IAHH-8015BG I	2748	-2.48	-2.94	3.92	26	82	56
16	IAHH-8016BG II	2478	-2.64	-7.73	8.21	64	150	86
17	IAHH-8017BG I	2493	4.72	-5.54	7.42	58	141	83
18	IAHH-8018BG I	3019	-6.27	-9.66	11.67	88	122	34
19	IAHH-8019BG I	3139	2.14	-8.13	8.43	68	92	24
20	IAHH-8020BG I	2984	-2.87	-5.4	6.17	44	82	38
21	IAHH-8021BG I	2680	-5.17	-13.41	14.45	101	167	66
22	IAHH-8022BG II	2290	6.28	-4.01	7.69	61	154	93
23	IAHH-8023BG II	1862	1.53	-19.99	20.06	109	216	107
24	IAHH-8024BG II	2027	6.73	-10.06	12.27	92	193	101
25	IAHH-8025BG II	2487	-0.07	0.65	0.65	3	88	85
26	IAHH-8026BG II	2532	7.77	-1.59	8.26	66	146	80
27	IAHH-8027BG II	2498	0.18	0.33	0.38	1	83	82
28	IAHH-8028BG II	2298	2.03	-0.89	2.3	14	106	92
29	IAHH-8029BG II	2862	-7.32	-3.14	8.26	65	113	48
30	IAHH-8030BG II	2039	6.2	-1.17	6.58	47	147	100
31	IAHH-8031BG II	2530	-9.07	-6.85	11.68	89	170	81
32	IAHH-8032BG II	2842	-6.33	1.26	6.72	52	102	50
33	IAHH-8033BG II	2728	3.03	3.86	4.99	32	93	61
34	IAHH-8034BG II	3075	0.96	-4.33	4.45	27	56	29
35	IAHH-8035BG II	2741	1.29	1.34	1.9	10	69	59
36	IAHH-8036BG I	3164	12.22	2.52	13	95	117	22
37	IAHH-8037BG II	3025	10.45	-0.3	10.91	78	111	33
38	IAHH-8038NBt	2324	5.19	-7.65	9.37	72	162	90
39	IAHH-8039BG I	4095	-3.96	9.28	10.16	76	77	1

Sl no	Hybrids	SCY (kg/ha)	AMMI Stability estimates					
			IPCA 1	IPCA 2	ASV	Rank ASV	YSI	Rank YSI
40	IAHH-8040BG I	3485	-3.07	5.07	6	41	50	9
41	IAHH-8041BG I	3717	0.54	6.63	6.66	50	53	3
42	IAHH-8042BG I	3428	-1.7	9.65	9.81	74	86	12
43	IAHH-8043BG II	2908	-11.33	-8.66	14.65	102	146	44
44	IAHH-8044BG II	2448	-2.97	0.39	3.13	20	108	88
45	IAHH-8045BG II	2961	-2.67	0.61	2.85	17	58	41
46	IAHH-8046BG II	3528	-11.88	4.52	13.19	97	103	6
47	IAHH-8047BG II	3313	-6.07	4.48	7.76	62	77	15
48	IAHH-8048BG II	3191	-4.36	7.64	8.9	70	90	20
49	IAHH-8049BG II	3410	-11.49	-5.09	13.02	96	109	13
50	IAHH-8050BG II	2997	6.91	1.82	7.43	60	97	37
51	IAHH-8051BG II	2245	3.82	-13.04	13.63	98	192	94
52	IAHH-8052BG II	2879	3.76	-3.64	5.36	35	80	45
53	IAHH-8053BG II	3288	-5.42	-5.49	7.88	63	80	17
54	IAHH-8054BG II	2492	10.1	3.01	10.96	79	163	84
55	IAHH-8055BG II	2723	0.42	0.78	0.9	4	66	62
56	IAHH-8056BG II	2623	1.61	1.1	2.01	11	82	71
57	IAHH-8057BG II	2580	1.97	4.22	4.7	28	106	78
58	IAHH-8058BG II	2204	-1.38	-6.05	6.22	45	140	95
59	IAHH-8059BG II	2146	0.66	-9.42	9.44	73	170	97
60	IAHH-8060BG II	2745	-6.26	-0.96	6.6	48	106	58
61	IAHH-8061BG II	3128	0.98	2.54	2.74	16	41	25
62	IAHH-8062BG II	2821	7.55	-8.58	11.65	87	139	52
63	IAHH-8063BG II	2763	-1.57	-5.31	5.56	36	90	54
64	IAHH-8064BG II	2752	-0.08	6.69	6.69	51	106	55
65	IAHH-8065BG II	2183	1.43	-0.95	1.77	8	104	96
66	IAHH-8066BG II	2003	11.07	0.96	11.59	86	191	105
67	IAHH-8067BG II	2868	-0.42	6.47	6.49	46	93	47
68	IAHH-8068BG II	2584	-1.91	4.44	4.87	31	108	77
69	IAHH-8069BG II	2366	2.53	7.93	8.36	67	156	89
70	IAHH-8070BG II	2627	1.79	3.23	3.73	24	94	70
71	IAHH-8071BG I	2747	-0.87	0.3	0.96	5	62	57
72	IAHH-8072BG II	2093	1.71	2.23	2.85	18	116	98
73	IAHH-8073BG I	2764	-4.1	11.59	12.35	94	147	53
74	IAHH-8074BG I	3055	0.59	5.83	5.86	39	71	32
75	IAHH-8075BG I	2853	2.9	4.04	5.05	33	82	49
76	IAHH-8076BG I	2838	2.81	1.72	3.4	21	72	51
77	IAHH-8077BG I	3066	2.67	5.16	5.87	40	71	31
78	IAHH-8078BG I	3434	-0.34	5.56	5.57	37	48	11
79	IAHH-8079BG II	2948	-4.06	3.79	5.68	38	80	42
80	IAHH-8080BG I	3085	-17.35	0.16	18.11	108	136	28

Sl no	Hybrids	SCY (kg/ha)	AMMI Stability estimates					
			IPCA 1	IPCA 2	ASV	Rank ASV	YSI	Rank YSI
81	IAHH-8081BG I	3774	-11.72	0.77	12.25	91	93	2
82	IAHH-8082BG I	3507	-7.09	8.47	11.25	82	90	8
83	IAHH-8083BG I	3625	-13.36	2.49	14.16	100	104	4
84	IAHH-8084BG I	3443	-16.1	-4.17	17.31	107	117	10
85	IAHH-8085BG II	3293	-10.7	-1.12	11.22	81	97	16
86	IAHH-8086BG II	2019	-3.24	-10.89	11.4	85	187	102
87	IAHH-8087BG II	2086	8.91	-6.56	11.38	83	182	99
88	IAHH-8088BG II	2695	-0.7	11.77	11.79	90	153	63
89	IAHH-8089BG II	3012	-1.84	15.12	15.24	103	139	36
90	IAHH-8090BG II	2615	-1.13	4.56	4.71	29	101	72
91	IAHH-8091BG II	2731	-5.17	4.4	6.97	54	114	60
92	IAHH-8092BG II	3073	1.48	3.06	3.43	22	52	30
93	IAHH-8093BG II	1646	13.56	-8.21	16.36	106	215	109
94	IAHH-8094BG II	2015	11.74	-0.96	12.29	93	196	103
95	IAHH-8095BG II	2872	6.78	8.39	10.97	80	126	46
96	IAHH-8096BG II	2981	-1.27	-0.02	1.32	6	45	39
97	IAHH-8097BG II	3018	4.07	6.09	7.42	59	94	35
98	IAHH-8098BG II	2611	8.79	1.63	9.31	71	144	73
99	IAHH-8099BG I	2600	6.15	3.24	7.19	56	132	76
100	IAHH-8100BG II	2968	7.09	8.66	11.4	84	124	40
101	IAHH-8101NBt	2314	6.13	-7.45	9.82	75	166	91
102	IAHH-8102BG I	3525	-1.63	0.56	1.79	9	16	7
103	IAHH-8103BG I	3096	4.57	0.39	4.79	30	56	26
104	IAHH-8104BG I	3209	11.79	6.03	13.7	99	118	19
105	IAHH-8105BG I	3090	9.76	11.66	15.49	104	131	27
106	Ajeet 155 BGII check	2685	0.39	-6.77	6.79	53	118	65
107	Jadoo BGII check	2912	-0.95	1.92	2.16	13	56	43
108	DHH-11	1967	-0.29	-0.25	0.39	2	108	106
109	Non Bt Variety	1738	6.53	-2.5	7.26	57	165	108
	Aurangabad	3192	-0.46	51.87				
	Dharwad	3030	-45.65	-26.33				
	Raichur	2139	46.11	-25.54				

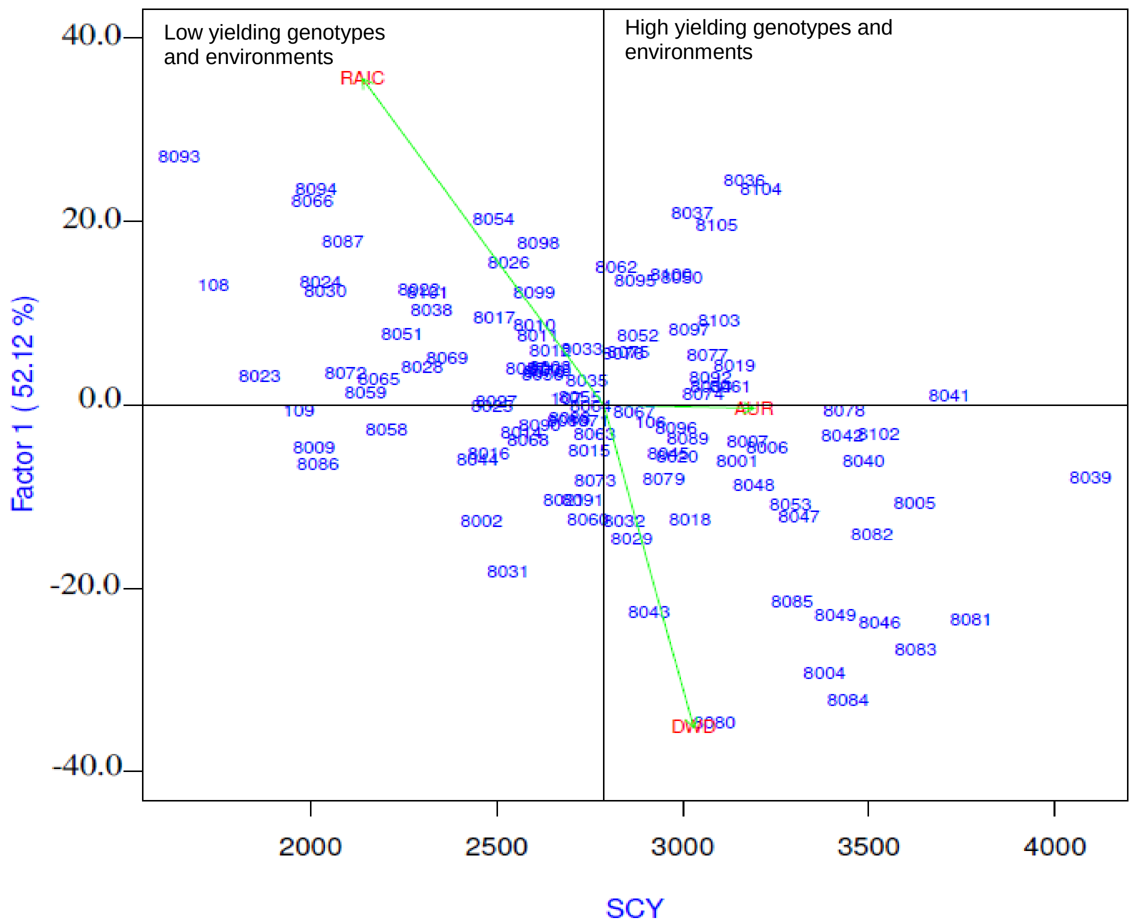

Figure 1. AMMI I biplot based on seed cotton yield over main principal component (IPCA 1) values.

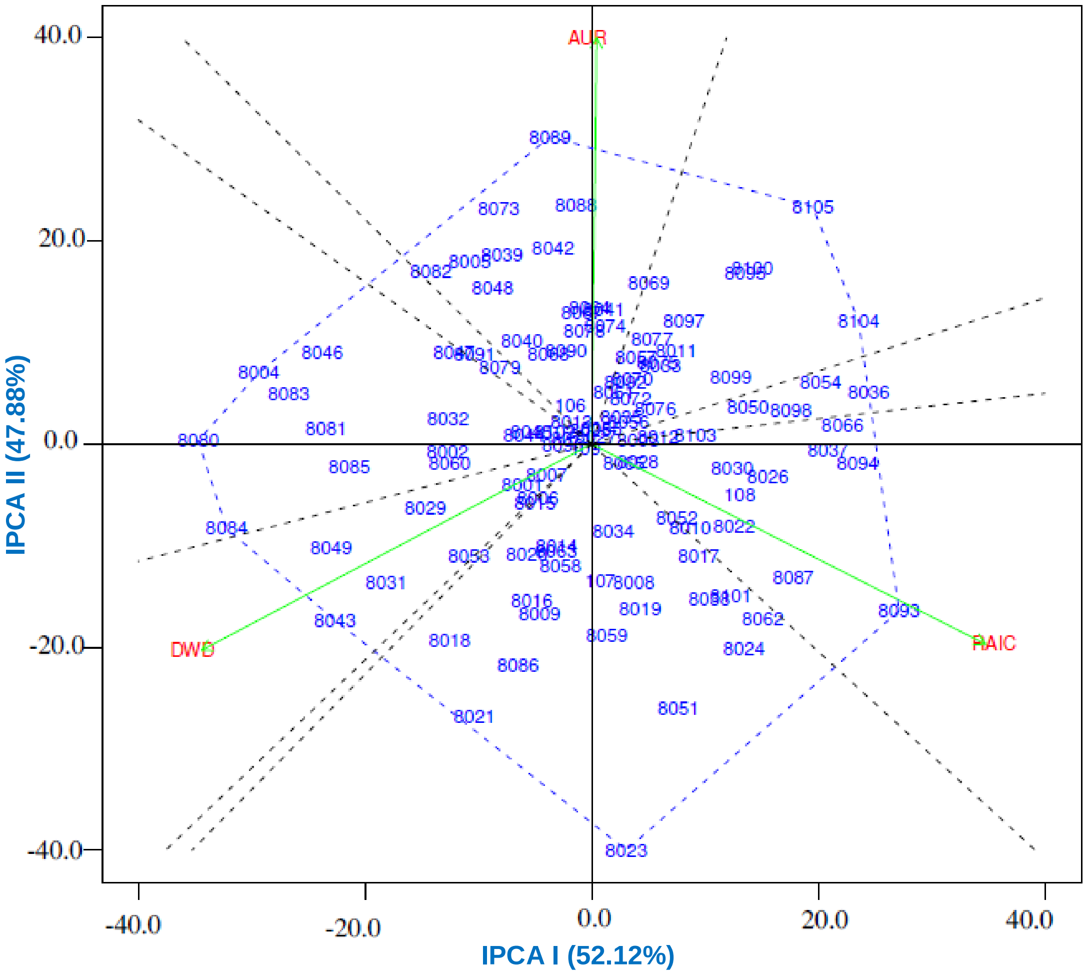

Figure 2. AMMI 2 biplot based on seed cotton yield over 3 locations

3.2. **AMMI analysis**

The AMMI stability values (ASV) and their corresponding ranks for the tested genotypes are presented in Table 3. In the AMMI model, GEI was explained by principal component analysis [19] that maximizes the variation explained by the products of the genotypic and environmental scores. A desirable property of AMMI analysis is that genotype and environment scores can be used to construct a powerful graphical representation as a biplot (Figure 2 and 3). In biplot genotypes that were more similar to each other were close to each other in the plot. The angle between environmental axes was related to the correlation between environments. An acute angle indicates the positive correlation, an obtuse angle indicates the negative correlation (like Aurangabad and Dharwad; Aurangabad and Raichur; Dharwad and Raichur).

The discriminating ability of the environments can be judged by calculating the distance of each environment from the biplot origin [5,7 and 19]. In this regard, the environments E1, E2 and E3 were most discriminating as indicated by the long distance from the biplot origin. The high potential environment E2 (Dharwad) can be seen in quadrant-II, with minimum interaction effects, high negative IPCA I (-45.65) as well as IPCAII (-26.33) scores. The low potential environments E-3, (Raichur) distributed in the quadrant- IV, with high positive IPCA I (46.11) score too low negative IPCA-2 (-25.34) scores. The E-1 showed the second-highest yield potentiality, had negative IPCA I (-0.46) and high positive IPCA-2 (51.87) scores. Thus, the biplot indicated E-2 and E-1 as the high yielding environment and E-3 as the low yielding environment. The cotton hybrids genotypes also showed wide variability in yield. Similarly, sites with IPCA I scores near zero had little interaction across genotypes and low discriminating ability among genotypes [3,6 and19]. According to Gauch and Zobel [8], if genotypes and environments are close in any graph area, it will show specific adaptability of a genotype to the environment *i.e.,* genotypes that were close to the nearby environment will perform better in those specific environments than that genotype which was far away. Likewise, IAHH-8031 BGII, IAHH-8001 BGII and IAHH-8043 BGII were positively related to Dharwad location same way IAHH- 8080 BGI, IAHH-8042 BGI, IAHH-8069 BGII and IAHH- 8074 BGI were suitable for Aurangabad location.

From biplot Figure 1, biplot constructed from IPCA I and mean performance of the hybrids from across the locations. The IPCAI scores of a genotype in the AMMI analysis were an indication of the stability or adaptation over environments. The greater the IPCA scores, either negative or positive, (as it is a relative value), the more specific adapted is a genotype to certain environments. The IPCAI scores approximate zero, the genotype will be more stable or adapted to the environments sampled.

AMMI biplot II (Figure 2) was constructed from both IPCA values (PC1 and PC2) and it quantifies stability using AMMI stability value (ASV). ASV is the distance from the vertex of IPCA I and IPCA II to the genotypes or environments that fall in the AMMI II biplot graph. This value used to measure the seed cotton yield stability of the genotype and cluster the genotypes and environments into different groups. Genotypes or environments which were very close to the vertex were more stable than those genotypes or environments away from the vertex. In other words, genotypes or environments that had less value of ASV score tend to be more stable than those genotypes or environments that had high ASV scores. From AMMI biplot II (Figure 2), hybrids IAHH-8023 BGII, IAHH-8080 BGI, IAHH-8105 BGI and IAHH-8094 BGII were far from the origin and considered to be unstable. On the other hand, genotypes Ajeet -155 BGII, IAHH-8102 BGI, IAHH-8061 BGII were close to the origin and considered stable. Likewise, out of 109 hybrids, 57 hybrids were stable with IPCA scores near zero. However, out of 57 hybrids, 18 hybrids with high mean yield and low ASV scored hybrids were recommended for across the environments (IAHH 8096 BGII, Jadoo BGII, IAHH-8007 BGII, IAHH-8061BGII, IAHH-8045 BGII, IAHH-8092 BGII, IAHH-8102 BGI, IAHH-8006 BGII, IAHH-8001 BGII, IAHH-8034 BGII, IAHH-8041 BGI, IAHH-8052 BGII, IAHH-8075 BGI and IAHH-8103 BGI). The fact that 57 hybrids were stable across locations reflects that the *Bt* event that brings bollworm resistance also contribute to the stability of the hybrids. It is known that genetic background play's an important role in the yielding ability of the hybrids, but nullified bollworm infestation has contributed significantly to the stability of hybrids [22]. Based on Biplot (Figure 2 and Table 4), genotypes were grouped into 4 groups based on their distribution to quadrants [5, 11, 20, 21 and 23].

Group, I the hybrids plotted the right side of the central axis formed based on grand mean which exhibited high seed cotton yield compared to the left side of the axis. Nineteen cotton hybrids recorded above-average performance with a positive interaction effect was present in quadrant I. Among nineteen hybrids, ten hybrids were BG II with an average mean of 2986 kg/ha and nine BGI cotton hybrids with 3153 kg/ha of seed cotton yield. Among BG I hybrids, IAHH-8102 BGI recorded low ASV values (1.79) with a mean seed cotton yield of 3525 kg/ha but the yield stability index was 16 with the rank of 17. As YSI takes the stability along with mean cotton yield into consideration, low YSI was recorded in IAHH-8041 BGI (YSI-53, SCY- 3717 kg/ha, ASV- 6.66) which indicated hybrid moderate stability across the environment, whereas maximum ASV value recorded in IAHH-8105 BGI (ASV-15.49, SCY-3090 kg/ ha) but YSI was 131, indicating genotype was highly interacting with the environment and suitable for the favorable environment. Among the BGII hybrids, low ASV value recorded in IAHH-8061 BGII (ASV- 2.74, SCY- 3128 kg/ha, YSI- 41) indicated the stable hybrid across the test environment followed by IAHH-8092 BGII (ASV-3.43, SCY- 3073 kg/ha, YSI- 52) and IAHH-8034 BGII (ASV-4.45, SCY-3075 kg/ha, YSI- 56). The hybrid, IAHH-8100 BGII recorded a maximum ASV value of 11.4 (SCY- 2968 kg/ha, YSI-124) representing the interaction with the environment and adaptability for a specific environment.

Group II comprises 36 hybrids that were plotted on the II quadrant along with Raichur also. All the hybrids were low yielder than the grand mean. ASV values ranged from 0.38 to 20.06 and YSI values ranged from 66 to 216. In group III, 23 hybrids were plotted on the III quadrant with lower the grand mean and exhibiting negative interaction. Their ASV values ranged from 0.39 to 14.45 and YSI values scored from 62 to 187.

In group IV, a total of 31 hybrids plotted on the IV quadrant with above-average seed cotton yield but having a negative interaction effect. Among 31 hybrids, 19 and 12 cotton hybrids were BG II and BG I respectively. In BGI hybrids, the least YSI was from IAHH-8102 BG I (YSI-16, ASV- 1.79, SCY-3525 kg/ha) followed by IAHH-8078 BGI (YSI-48, ASV-5.57, SCY-3434 kg/ha) and IAHH-8040 BGI (YSI-50, ASV-6, SCY-3485 kg/ha) and relatively stable but interacting negatively. Likewise, in BGII hybrids, least YSI values recorded from IAHH-8007 BGII (YSI-36, ASV-2.56, SCY- 3174 kg/ha), IAHH-8006 BGII (YSI-41, ASV-3.65, SCY- 3225 kg/ha), IAHH-8096 BGII (YSI-45, ASV-1.32, SCY-2981 kg/ha), Jadoo BGII (YSI-56, ASV-2.16, SCY-2912 kg/ha) and IAHH-8045 BGII (YSI-58, ASV-2.85, SCY-2961 kg/ha).

4. CONCLUSION

Significant variability among the genotypes and genotypes × environments indicated that hybrids were from diverse genetic backgrounds and hybrids had variable performance in different locations. IPCA scores nearing zero and low ASV values brought out the high frequency of hybrid (57) as stable irrespective of mean yield. *Bt* cotton resistance to bollworm has contributed stability of more frequency of hybrids as it nullified variation of bollworm infestation in each of the locations. The distance from the origin and placement of locations in different quadrants of the biplot reflected that the locations were substantially discriminatory. The hybrids IAHH-8102 BGI, IAHH-8061 BGII, IAHH-8092 BGII and IAHH-8096 BGII were acknowledged high yielding and stable across diverse locations are recommended for further evaluation and commercialization.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly used products in our area of research and country. There is no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by the personal efforts of the authors.

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