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ELUCIDATING PERFORMANCE OF CHILLI GERMPLASM BELONGING TO THREE *CAPSICUM* SPECIES THROUGH PRINCIPAL COMPONENT ANALYSIS AND SELECTION OF HETEROTIC INTERSPECIFIC HYBRID

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ABSTRACT

The present study was carried out to assess genetic variability among genotypes of three different chilli species- *C. annuum, C. chinense* and *C. frutescens* in outdoor field environment and polyhouse environment to identify a suitable environment to perform interspecific hybridization amongst these species. Heterosis of the F_1 interspecific hybrids was predicted for future crop improvement programmes.

The results of variability study exhibited a significant variation amongst the parental genotypes. Most of the characters were found to have high heritability coupled with high genetic advance which is an indication of additive gene effects and may be considered as selection criteria. Significant positive correlation was observed for fresh fruit yield/plant and its attributing traits except for the traits number of primary branches/ plant and number of fruits/plant. Cluster analysis divided the genotypes into two main clusters. The Principal Component analysis in two environments- outdoor field and polyhouse environment showed that the contribution of the different characters to the variability was comparable in both environments.

The crossing program was thus conducted in the outdoor field environment to study heterosis for interspecific hybridization, where Mem x King chilli-A5 was found to be the most desirable interspecific hybrid.

Key words : King chilli, Interspecific hybridization, Genetic diversity analysis, Principal Component analysis, Heterosis.

Introduction

King chilli is a very important spice crop in the North Eastern region of India, due to its many medicinal and therapeutic properties and its high pungency. Chilli is a spice crop, which originated in South and Central America. It belongs to the family Solanaceae and genus *Capsicum* consisting of around 30 species, five of which are domesticated species- *C. annuum* L., *C. frutescens* L., *C. chinense* Jacq., *C. baccatum* L. and *C. pubescens* Ruiz & Pav. (Barboza *et al*., 2022).The crop is popular due to its pungent property (Naseem *et al*., 2024). Majority of the cultivars grown in Asia, Central and Latin American countries are pungent, while less pungent and non-pungent types are popular in European countries. Capsaicin, the active hot principle is used in pharmaceutical, cosmetic, food and drinks. Besides these properties chilli is a rich source of metabolites such as provitamin A, vitamins C, E, essential micro- and macro nutrients, capsaicinoids which are beneficial for human health (Olatunji *et al*., 2020). Chilli has good anti-oxidant property with scavenging ability to free radicals and oxygen; it is also effective against coagulation, obesity, diabetes, inflammation, microbial diseases and diseases such as cancer (Bal *et al*., 2022).

King chilli (Bhut jolokia) is a high value crop, but is susceptible to various diseases caused by bacteria, fungi and/or virus. On the other hand, the locally adapted genotypes Krishna and Mem are tolerant to such diseases. Capsicum (bell pepper) has large fruit with less pungency compared to other genotypes included in the present study.

Therefore, to exploit the transfer of resistance traits from locally adapted genotypes and fruit quality traits from Capsicum to King chilli interspecific hybridization can be opted for. A study of the Genetics of the characters and their interrelation are important for a successful breeding program. Besides, in interspecific hybridization, the species must be genetically close, minimizing problems of incompatibility thus enabling hybridization (Hazarika *et al*., 2023).

Keeping in view the above, the purpose of the present study was to elucidate the genetics of some selected traits for successful introgression of traits such as disease resistance and fruit quality through interspecific hybridization between the species *C. annuum*, *C. frutescens* and *C. chinense*. The variability study was conducted in two different environments namely field condition and polyhouse environment to compare the character expression of yield attributing traits and select a suitable environment for interspecific hybridization.

Materials and Methods

The experimental material for the present investigation included eight different genotypes comprising of two *C. annuum* (Capsicum, *Krishna*), five *C. chinense* (King chilli accessions, namely A1, A5, A18, A19, A20) and one *C. frutescens* (Mem) species. The study was conducted in the Horticulture Research Farm of Assam Agricultural University, Jorhat-13 (Supplementary Table S1) during Rabi, 2018-19 and Rabi, 2019-20. Records were taken for twelve biometrical traits such as Plant height (cm), Number of primary branches, Days to first flowering, Days to 50% flowering, Number of fruits per plant, Length of fresh fruit (cm), Length of dry fruit (cm), Girth of fresh fruit (cm), Girth of dry fruit (cm), Fresh fruit weight (g), Dry fruit weight (g), Number of seeds per fruit, 100 seed weight (g), Fresh Fruit yield per plant (g) and Dry fruit yield per plant (g). Randomized block design was followed with five replications in the field for taking observations. The mean values of the observations recorded for yield and yield attributing traits were subjected to statistical analysis such as Analysis of Variance, estimation of variability parameters, heritability, genetic advance, correlation coefficient, path coefficient analysis, cluster analysis. The experiment was also conducted under polyhouse conditions with five replications. Principal Component Analysis (PCA) was done to draw a comparative between the two environments and assess the variation in character expression in the two environments. Interspecific hybridization was carried out to analyze heterosis in terms of mid-parent heterosis.

Results and Discussion

Analysis of variance for parental genotypes

The results of analysis of variance studied for the characters under study (Supplementary Table S2) revealed significant differences among the genotypes indicating the presence of variability among the species

Supplementary Table S1 : Meteorological data during the period of experimentation.

Period	Temperature (^{O}C)		RH(%)		Total BSSH (hrs.)	Total Rinfall (mm)
	Maximum	Minimum	Morning	Evening		
2018						
October	29.6	20.5	96.8	69.3	165.9	17.4
November	26.7	14.9	97.6	65.9	183.5	32.4
December	24.9	10.9	97.5	63	203.1	29.6
2019						
January	24.6	9.2	95	61.1	215.7	10.7
February	24.8	12.4	94.3	63.5	126.9	36
March	27	15.7	91.2	61.3	120	77.2
April	28.9	19.8	91.9	69.9	123.2	177.4
October	30.1	21.6	97.2	72.1	155.8	251.7
November	28.5	17.3	97.4	66.9	191.3	11.5
December	23.9	10.3	99.2	63.4	162.6	1.3
2020						
January	22.6	9.8	99.4	63.5	136.6	29.6
February	24.9	12	97.1	59.3	131.6	11.1
March	28.8	15.9	93.1	61	179.7	6.4
April	29.1	17.6	93.1	66	143.7	107.2

Supplementary Table S2 : Analysis of variance for parental population.

	Df	Plant height (cm)	Number of primary branches per plant	Days to first flowering	Days to 50% flowering	Number of fruits per plant	Length of fresh fruit (cm)	Length of dry fruit (cm)	Girth of fresh fruit (cm)	Girth of dry fruit (cm)	Fresh fruit weight (g)	Dry fruit weight (g)	Number of seeds per fruit	100 seeds weight (g)	Dry fruit yield per plant (g)	Fresh fruit yield per plant (g)
Replication	2	30.232	0.293	8.719	7.271	31.733	0.296	0.091	0.284	0.67	3.144	1.309	452.613	0.005	5307.301	1330.144
Treatment	7	439.303*	2.480*	141.023*	261.352*	1310.862*	18.083*	12.496*	24.543*	15.177*	228.521*	61.392*	3849.855*	0.110*	54693.200*	173761.103*
Error	14	7.078	0.144	8.745	19.095	15.295	0.614	0.461	0.311	0.478	11.691	3.63	325.122	0.003	5555.314	6060.63
C.V (%)		3.105	11.615	4.704	5.453	9.272	13.277	15.9	18.428	27.3	44.901	50.866	39.457	8.337	83.081	29.013

*significant at 5% level of significance **significant at 1% level of significance.

with respect to plant height (cm), number of primary branches, days to first and 50% flowering, number of fruits per plant, length of fresh and dry fruit (cm), girth of fresh and dry fruit (cm), fresh and dry fruit weight (g), number of seeds per fruit, 100 seed weight (g), dry fruit yield per plant (g) and fresh fruit yield per plant (g).

Mean performance of parental genotypes for agro-morphological traits

Estimation of mean performance of the parental species indicated wide range of variability among those species (Supplementary Table S3). The highest value for plant height was observed by the King chilli accession A19. Number of primary branches was found to be highest in King chilli accession A1. Lowest days to first flowering and 50% flowering were recorded in Krishna with a mean of 54.30 and 64.18 days respectively. The number of fruits per plant was highest in Mem. Capsicum exhibited the highest mean value among all the species for the fruit characters - Length of fresh and dry fruit, girth of fresh and dry fruit, fresh and dry fruit weight, number of seeds per fruit, 100 seed weight and dry fruit and fresh fruit yield per plant

However, mean performance cannot be the sole measurement for selection, so estimation of genetic parameters is necessary for identifying the selection criteria in breeding programmes.

Estimation of genetic parameters for agro-morphological traits

The results for estimation of genetic parameters are given in Table 1. The value for genotypic coefficient of variation (GCV) was found to be high for all the characters except plant height, days to first flowering and days to 50% flowering which showed moderate GCV. The trait dry fruit yield per plant (142.66%) showed the highest GCV, followed by dry fruit weight (117.14%), fresh fruit weight (111.64%), and girth of fresh fruit (93.94%).

The traits plant height, days to first flowering and days to 50% flowering showed moderate phenotypic coefficient of variation (PCV), while rest of the traits showed high PCV. The highest PCV was found for the trait dry fruit yield per plant (165.09%) followed by dry fruit weight (127.71%), fresh fruit weight (120.33%), girth of fresh fruit (95.73%).

Thus, magnitudes of phenotypic coefficient of variations were higher than corresponding genotypic coefficients of variation indicating presence of high environmental effects. Similar result was observed in the study of Sahu (2021) where magnitudes of phenotypic coefficient of variations were found to be higher than

Supplementary Table S3 : Estimation of mean performance of parental genotypes for agro-morphological traits.

	Plant height (cm)	Number of primary branches	Days to 1st flowering	Days to 50% flowering	Number of fruits per plant	Length of fresh fruit (cm)	Length of dry fruit (cm)
KING CHILLI-A1	75.7	4.37	75.18	91.95	44.61	6.5	3.74
KING CHILLI-A5	85.76	3.6	63.28	85.25	26.2	6.51	4.2
KING CHILLI-A18	89.77	4.07	67.22	88.71	37.07	7.56	6.42
KING CHILLI-A19	103.64	3.27	58.92	80.33	44.4	5.73	3.9
KING CHILLI-A20	102.6	4.07	57.33	75.48	36	6.72	4.73
KRISHNA	77.72	2.53	54.3	64.18	61.59	3.39	2.61
MEM	77.95	2.33	59	71.2	78.03	1.46	1.03
CAPSICUM	72.39	1.93	67.73	83.93	9.53	9.36	7.53
Mean	85.69	3.27	62.87	80.13	42.18	5.9	4.27
Range	72.39 - 103.64	1.93 - 4.37	54.3 - 75.18	64.18 - 91.95	9.53 - 78.03	1.46 - 9.36	1.03 - 7.53
SE (m)	1.536	0.219	1.707	2.523	2.258	0.453	0.392
C.D (5%)	4.704	0.672	5.229	7.727	6.915	1.386	1.201

	Girth of fresh fruit (cm)	Girth of dry fruit (cm)	Fresh fruit weight (g)	Dry fruit weight (g)	Number of seeds per fruit	100 seeds weight (g)	Dry fruit yield per plant (g)	Fresh fruit yield per plant (g)
KING CHILLI-A1	2.37	1.89	6.52	2.59	34.12	0.73	56.36	251.04
KING CHILLI-A5	2.88	2.6	7.26	3.15	34.93	0.77	28.53	158.97
KING CHILLI-A18	2.85	2.65	5.82	2.77	35.53	0.72	52.6	251
KING CHILLI-A19	2.06	1.73	5.37	2.26	41.53	0.62	61.19	222.75
KING CHILLI-A20	2.05	1.77	5.01	2.95	34.53	0.71	68.15	211.62
KRISHNA	1.15	0.97	1.67	0.96	34.13	0.46	20.92	105.14
MEM	0.95	0.79	0.79	0.58	18	0.31	10.04	100.83
CAPSICUM	9.89	7.85	28.47	14.7	132.8	0.92	419.9	845.31
Mean	3.03	2.53	7.62	3.75	45.7	0.66	89.71	268.33
Range	0.95 - 9.89	0.79 - 7.85	0.79 - 28.47	0.58 - 14.70	18.00-132.80	0.31 - 0.92	10.04-419.90	100.83-845.31
SE (m)	0.32	0.4	1.97	1.1	10.41	0.03	43.03	44.95
C.D (5%)	0.986	1.222	6.046	3.369	31.882	0.097	131.789	137.653

corresponding genotypic coefficients of variations.

All the traits under study were found to have high broad sense heritability; the trait number of fruits per plant (96.58%) exhibited the highest heritability.

The trait dry fruit yield per plant (253.95%) had the highest GA (% of mean) followed by dry fruit weight (221.35%) and fresh fruit weight (213.37%). Days to first flowering had moderate genetic advance as per cent of mean, while rest of the traits were found to have high genetic advance as per cent of mean

Most of the traits under study was observed to have high GCV, PCV with high heritability (broad sense) coupled with high GA (%) which may be considered as selection criteria. Similar result was observed in the study of Sahu (2021), Singh *et al*. (2022), Teju (2022) and Alam *et al*. (2024).

Character interrelationship and path coefficient analysis

Results of estimation of phenotypic and genotypic correlation coefficients among parental genotypes for the agro-morphological traits are given in Table 2. Besides, path coefficient analysis was carried out for partitioning the genotypic correlation coefficients between component traits and fresh fruit yield per plant (g) into direct and indirect effect on fresh fruit yield per plant as dependable variable (Table 3).

Length of fresh fruit (1.132) followed by number of fruits per plant (0.831) and fresh fruit weight (0.824) were showing high direct effect on fresh fruit yield with significant positive correlation. Thus, these traits may be used as indirect selection criteria for selecting genotypes with high fresh fruit yield per plant. Similar result was observed by Swetha *et al*. (2023) and Saisupriya *et al*.

Table 1 : Estimation of genetic parameters for agro-morphological traits in eight parental genotypes.

Characters	Range	GCV (%)	PCV (%)	h^2(bs)	GA (% of mean)
Plant height	72.39 - 103.64	14.01	14.35	95.32	28.17
No. of primary branches	1.93 - 4.37	26.98	29.37	84.36	51.05
days to 1st flowering	54.30 - 75.18	10.56	11.56	83.45	19.88
Days to 50% flowering	64.18 - 91.95	11.22	12.47	80.87	20.78
Number of fruits per plant	9.53 - 78.03	49.27	50.13	96.58	99.74
Length of fresh fruit	1.46 - 9.36	40.87	42.98	90.46	80.08
Length of dry fruit	1.03 - 7.53	46.90	49.52	89.69	91.50
Girth of fresh fruit	0.95 - 9.89	93.94	95.73	96.30	189.90
Girth of dry fruit	0.79 - 7.85	87.42	91.58	91.11	171.90
Fresh fruit weight	0.79 - 28.47	111.64	120.33	86.08	213.37
Dry fruit weight	0.58 - 14.70	117.14	127.71	84.14	221.35
Number of seeds per fruit	18.00 - 132.80	75.01	84.75	78.33	136.75
100 seed weight	0.31 - 0.92	28.86	30.04	92.30	57.12
Dry fruit yield per plant	10.04 - 419.90	142.66	165.09	74.67	253.95
Fresh fruit yield per plant	100.83 - 845.31	88.11	92.77	90.22	172.40

(2022), Chakrabarty and Islam (2017) in *C. annuum*.

The trait- number of fruits per plant had negative correlation with fresh fruit yield per plant. It is because indirect effect of the traits-number of primary branches, days to 50% flowering, length and girth of fresh fruit, fresh fruit weight and dry fruit yield per plant via this trait was found to be highly negative. Fresh fruit weight had positive correlation with yield/plant as the negative indirect effects of the traits-number of primary branches, days to first flowering, number of fruits per plant, dry fruit weight, number of seeds per fruit and 100 seed weight on fresh fruit yield per plant was low.

Moreover, fresh fruit yield had significant positive correlation with days to first flowering, dry fruit weight, seeds per fruit, 100 seed weight and dry fruit yield per plant, similar results were observed by Alam *et al*. (2024). When these interrelationships were divided into direct and indirect component effects, it was found that though days to first flowering, dry fruit weight, seeds per fruit, 100 seed weight had negative direct effects (-0.304, -0.187, -0.261 and -0.308, respectively). These negative direct effects were annulled by indirect effects of other traits.

On the other hand, fresh fruit yield showed significant negative correlation with number of primary branches per plant and number of fruits per plant. Similar study was conducted by Kumar *et al*. (2003) where number of fruits per plant was found to express negative correlation with length and girth of fresh fruit. Hence larger size of the fruits compensates for the lower number of fruits per plant. It was observed from the path coefficient analysis that the direct effect of these traits on fresh fruit yield were 0.126 and 0.831 respectively, but due to high negative effect of other traits via these traits, correlations were found to be significantly negative for fresh fruit yield per plant.

The residual effect for genotypic path coefficient analysis was found to be low (-0.014) which indicated that the component characters mostly accounted for variation in fruit yield per plant.

Cluster analysis

All the eight genotypes were screened for fifteen traits as listed for Analysis of Variance (ANOVA) for cluster analysis. As shown in the Dendrogram (Fig.1) the genotypes were clustered into two main clusters and sub-divided into four clusters, where Capsicum was found to be different from all the genotypes.

Principal component analysis (PCA)

The eight genotypes belonging to three different chilli species were grown in the field (outdoor environment) and inside the polyhouse (protected environment) for a comparative PCA to assess whether significant variation exists in the expression of traits in two contrasting environments for eleven traits listed in Tables below.

For outdoor field environment : Out of the 11 traits studied, only three principal components (PCs) exhibited more than one (>1) Eigen value and showed about 96.84% total cumulative variability among the traits (Table 4), thus these PCs were significant for further explanation. The Scree plot (Fig. 2) explained the percentage of variance associated between eigen values and principal components with each principal component (PC) and deduced that PC1 has a preponderance of

Table 2 : Estimation of Genotypic correlation coefficient among agro-morphological traits for eight parents.

Traits	Number of primary branches	Days to 1st flowering	Days to 50% flowering	Number of fruits per plant	Length of fresh fruit (cm)	Girth of fresh fruit (cm)	Fresh fruit weight (cm)	Dry fruit weight (g)	Number of seeds per fruit	100 seeds weight (g)	Dry fruit yield per plant (g)	Fresh fruit yield per plant (g)
Plant height	0.498*	-0.425*	-0.01	-0.06	0.09	-0.37	-0.36	-0.35	-0.37	0.03	-0.37	-0.35
Number of primary branches		0.39	0.571**	-0.14	0.29	-0.415*	-0.40	-0.440*	-0.522**	0.29	-0.534**	-0.426*
Days to 1st flowering			0.908**	-0.458*	0.590**	0.447*	0.480*	0.417*	0.34	0.619**	0.34	0.44*
Days to 50% flowering				-0.626**	0.748**	0.40	0.440*	0.37	0.27	0.746**	0.24	0.36
Number of fruits per plant					-0.980**	-0.795**	-0.813**	-0.793**	-0.758**	-0.993**	-0.752**	-0.759**
Length of fresh fruit (cm)						0.75**	0.80**	0.75**	0.68**	1.00**	0.66**	0.72**
Girth of fresh fruit (cm)							1.00**	1.00**	1.00**	0.75**	1.00**	1.00**
Fresh fruit weight (g)								1.00**	1.00**	0.80**	1.00**	1.00**
Dry fruit weight (g)									1.00**	0.77**	1.00**	1.00**
Number of seeds per fruit										0.71**	1.00**	1.00**
100 seed weight (g)											0.67**	0.73**
Dry fruit yield per plant (g)												1.00**

*significant at 5% level of significance **significant at 1% level of significance.

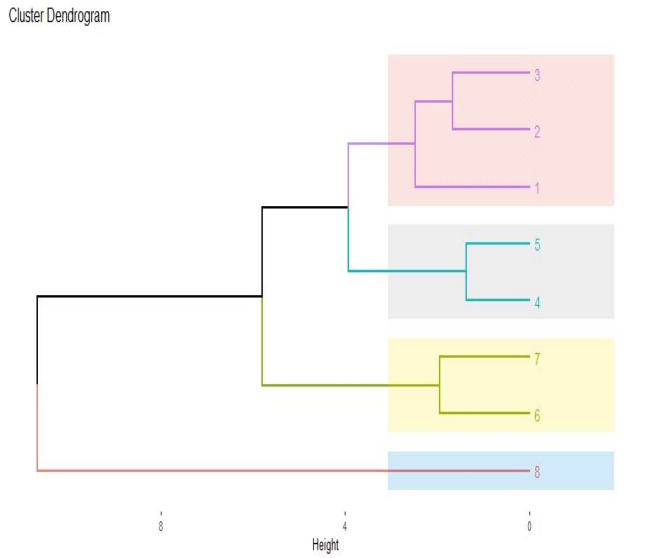

Fig. 1 : Dendogram resulting from cluster analysis of eight genotypes. (*where, 1= King Chilli-A1, 2= King Chilli-A5,3= King Chilli-A18, 4= King Chilli-A19, 5= King Chilli-A20, 6= Krishna, 7=Mem, 8=Capsicum).!

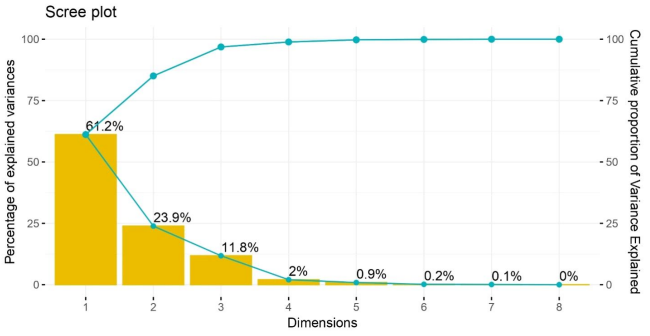

Fig. 2 : Scree plot showing Eigen values and percentage of cumulative variability under outdoor environment.

maximum variability of about 61.16% with the highest Eigen value of 6.73.Therefore, selection of genotypes and traits from PC1, PC2 and PC3 may be desirable. Analogous results were observed in the study by Singh *et al*. (2020).

The results presented in Table 4 revealed the yield related traits of PC1 donate a maximal share (61.16%) to the total variation (Fig. 3). The traits Fresh fruit weight (0.365), Girth of fresh fruit (0.362) and Fresh fruit yield per plant (0.357) showed highest positive contribution to the first PC, whereas number of fruits per plant (-0.348), plant height (-0.095) and number of primary branches (-0.036) contributed negatively.

PC2 accounted for 23.88% of the total variability. The highest positively related traits were number of primary branches (0.602), Days to 50% flowering (0.412) and plant height (0.312). While, number of seeds per fruit (-0.268), girth of fresh fruit (-0.203) and fresh fruit yield

Table 3 : Estimation of genotypic path coefficients of agro-morphological traits on fresh fruit yield per plant (g) for eight parents.

Trait	Plant height (cm)	Number primary of branches	Days to 1st flowering	Days to 50% flowering	Number of fruits per plant	Length of fresh fruit (cm)	Girth of fresh fruit (cm)	Fresh fruit weight (g)	Dry fruit weight (g)	Number of seeds per fruit	100 seed weight (g)	Dry fruit yield per plant (g)	Fresh fruit yield per plant (g)
Plant height (cm)	**-0.166**	0.063	0.129	0.000	-0.053	0.104	-0.053	-0.298	0.066	0.097	-0.010	-0.224	-0.350
Number of primary branches	-0.083	**0.126**	-0.117	0.019	-0.114	0.325	-0.060	-0.329	0.082	0.136	-0.090	-0.323	-0.426*
Days to 1st flowering	g0.071	0.049	**-0.304**	0.031	-0.380	0.667	0.064	0.397	-0.078	-0.089	-0.191	0.203	0.440*
Days to 50% flowering	0.002	0.072	-0.276	**0.034**	-0.520	0.846	0.058	0.365	-0.069	-0.070	-0.230	0.146	0.360
Number of fruits per plant	0.011	-0.017	0.139	-0.021	**0.831**	-1.110	-0.114	-0.674	0.148	0.198	0.306	-0.455	-0.759**
Length of fresh fruit (cm)	-0.015	0.036	-0.179	0.025	-0.815	**1.132**	0.108	0.659	-0.141	-0.178	-0.310	0.400	0.722**
Girth of fresh fruit (cm)	0.062	-0.052	-0.136	0.014	-0.661	0.840	**0.144**	0.841	-0.189	-0.261	-0.232	0.630	1.000**
Fresh fruit weight (g)	0.060	-0.050	-0.146	0.015	-0.676	0.900	0.140	**0.824**	-0.187	-0.267	-0.247	0.630	1.000**
Dry fruit weight (g)	0.059	-0.056	-0.127	0.013	-0.659	0.844	0.145	0.821	**-0.187**	-0.263	-0.237	0.650	1.000**
Number of seeds per fruit	0.062	-0.066	-0.104	0.009	-0.630	0.774	0.144	0.847	-0.189	**-0.261**	-0.220	0.633	1.000**
100 seed weight (g)	-0.005	0.037	-0.188	0.025	-0.825	1.140	0.108	0.664	-0.144	-0.186	**-0.308**	0.408	0.725**
Dry fruit yield per plant (g)	0.062	-0.067	-0.102	0.008	-0.620	0.735	0.150	0.924	-0.204	-0.281	-0.208	**0.604**	1.000**

Table 4 : Eigenvalue, contribution of variability and factor loadings for the principal component axes in outdoor environment.

Parameters	Principal Components (PCs)			
	1	2	3	4
Eigenvalue	6.728	2.627	1.298	0.224
Variability (%)	61.163	23.880	11.796	2.033
Cumulative variability (%)	61.163	85.043	96.840	98.873
Traits	**Factor loadings after Varimax rotation**			
Plant height	-0.095	0.312	-0.684	0.580
No. of primary branches	-0.036	0.602	0.014	-0.219
Days to 1st flowering	0.238	0.266	0.567	0.241
Days to 50% flowering	0.241	0.412	0.280	0.395
No. of fruits per plant	-0.349	-0.132	0.256	0.384
Length of fresh fruit (cm)	0.348	0.216	-0.184	-0.149
Girth of fresh fruit (cm)	0.363	-0.203	-0.028	0.081
Fresh fruit weight (g)	0.365	-0.192	-0.034	0.089
No. of seeds per fruit	0.342	-0.269	-0.094	0.097
100 seed weight (g)	0.350	0.214	-0.143	-0.344
Fresh fruit yield (g)	0.357	-0.201	-0.026	0.298

Table 5 : Contribution of the parental chilli genotypes to the first three principal component axes in outdoor environment.

Genotypes	PC1	PC2	PC3	PC4
King Chilli-A1	0.862	14.698	35.860	0.013
King Chilli-A5	0.305	4.192	0.093	17.661
King Chilli-A18	0.506	11.695	0.403	1.144
King Chilli-A19	0.960	0.905	14.731	29.421
King Chilli-A20	0.624	4.501	26.703	2.012
Krishna	11.640	15.587	0.069	24.243
Mem	18.850	14.073	9.620	12.630
Capsicum	53.753	21.849	0.023	0.376

per plant (-0.201) were negatively related. Hence, the traits falling in these PCs may be given due importance in chilli breeding. A similar verdict of variability was obtained for *C. frutescens* by Ema (2021).

PC3 had 11.80% contribution towards variability with Eigen value 1.298. the traits-number of primary branches, days to 1st and 50% flowering and number of fruits per plant were showing positive contribution.

The vectors (Fig. 3) in the first quadrant, viz., days to first flowering, days to 50% flowering, Length of fresh fruit and 100 seed weight were strongly correlated among

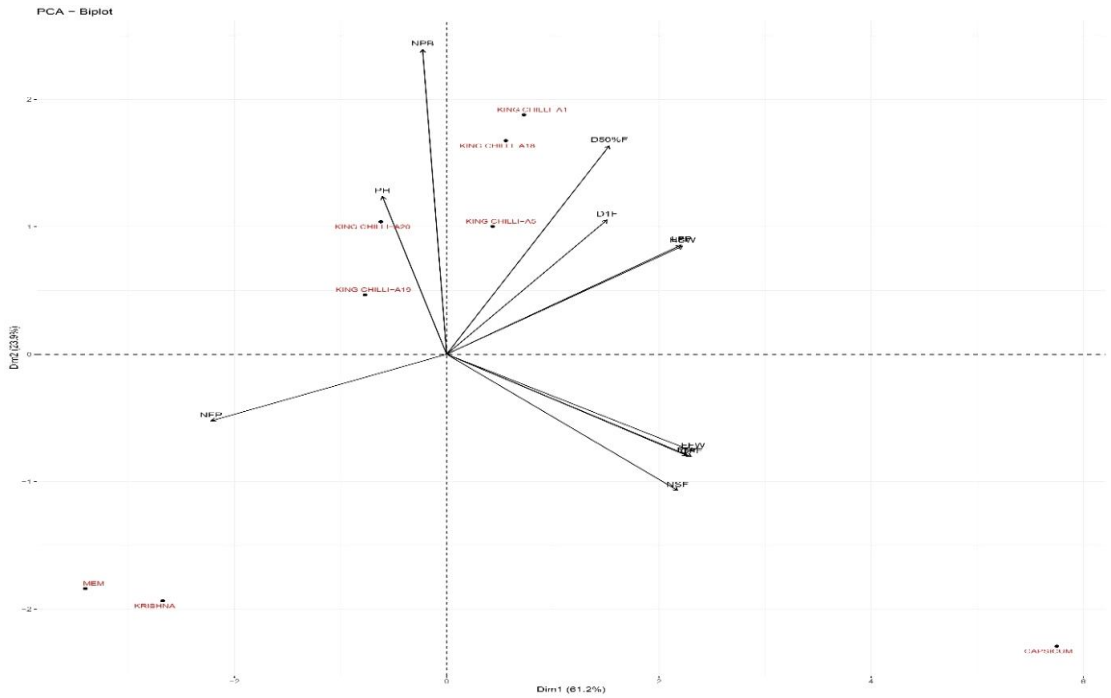

Fig. 3 : Distribution genotypes and traits across first two components based on PCA for outdoor environment.

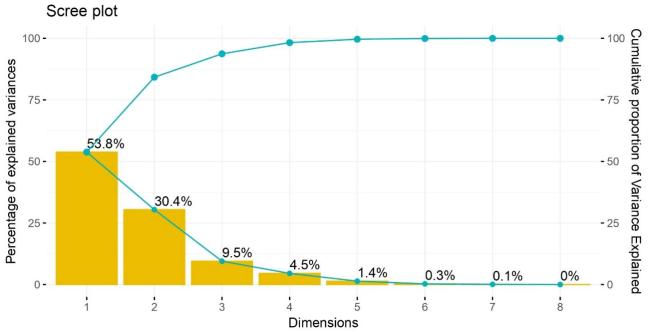

Fig. 4 : Scree plot showing Eigen values and percentage of cumulative variability under polyhouse environment.

themselves and loaded on the PC3, PC2, PC1 and PC1 respectively. The vectors in the second quadrant-Plant height and Number of primary branches were highly correlated variables loaded on PC4 and PC2 respectively. There exists only one vector-Number of fruits per plant in the third quadrant which was having weak correlation with the other traits and was loaded in PC4. In the fourth quadrant, Fresh fruit weight, Girth of fresh fruit, Fresh fruit yield; and Number of seeds per fruit loaded on PC1 were highly interrelated.

The genotypes King chilli accessions A1, A5 and A18 projected on the vectors of Number of primary branches and Days to 50% flowering were closest to them; while accession A19 and A20 were projected on the vectors of Plant height and Number of fruits per plant, indicating a positive interaction (Table 5). The genotypes Krishna and Mem were found to be superior for Number of fruits per plant. Whereas, Capsicum was found to had a positive interaction with Fresh fruit weight, Girth of fresh fruit, Fresh fruit yield; and Number of seeds per fruit. The genotypes with a high positive principal component score for PC1 were Capsicum (53.75), Mem (18.85), Krishna (11.64) and King chilli-A19 (0.96).

For polyhouse environment : PCA analysis was also carried out also for polyhouse condition. Similar to the above analysis, three principal components (PCs) exhibited more than one (>1) Eigenvalue and showed about 93.71% total cumulative variability among the traits (Table 6), thus PC1, PC2 and PC3 were significant for further explanation. PC1 has a preponderance of maximum variability of about 53.80% with the highest Eigenvalue 5.92 (Fig. 4). Therefore, selection of genotypes and traits from PC1 may be desirable. Similar results were observed by Singh *et al.* (2020).

The traits number of fruits per plant (0.380), Plant height (0.077) and number of primary branches (0.015) contributed positively to PC1, while traits- Fresh fruit weight (-0.389), No. of seeds per fruit (-0.388), Girth of fresh fruit (-0.384), etc. were negatively contributing to PC1.

The vectors (Fig. 5) in the first quadrant, viz., days to first and 50% flowering (loaded on PC4), Length of fresh fruit and 100 seed weight were strongly correlated among themselves and loaded on the PC3. The vectors in the second quadrant, Plant height and Number of primary branches were highly correlated variables loaded on PC3. There exists only one vector-Number of fruits

Table 6 : Eigenvalue, contribution of variability and factor loadings for the principal component axes under polyhouse environment.

Parameters	Principal Components (PCs)			
	1	2	3	4
Eigenvalue	5.918	3.346	1.044	0.499
Variability (%)	53.801	30.415	9.495	4.535
Cumulative variability (%)	53.801	84.217	93.711	98.247
Traits	**Factor loadings after Varimax rotation**			
Plant height	0.077	-0.307	0.686	0.552
No. of primary branches	0.015	-0.490	0.024	-0.540
Days to 1st flowering	-0.061	-0.482	-0.405	0.211
Days to 50% flowering	-0.084	-0.462	-0.392	0.402
No. of fruits per plant	0.380	0.133	-0.244	0.143
Length of fresh fruit (cm)	-0.364	-0.160	0.319	-0.094
Girth of fresh fruit (cm)	-0.384	0.178	-0.084	0.021
Fresh fruit weight (g)	-0.389	0.154	-0.094	0.115
No. of seeds per fruit	-0.388	0.159	0.018	0.187
100 seed weight (g)	-0.327	-0.283	0.082	-0.315
Fresh fruit yield (g)	-0.386	0.126	-0.163	0.141

per plant in the third quadrant which was having weak correlation with the other traits and was loaded in PC1. In the fourth quadrant, Girth of fresh fruit; Fresh fruit weight (loaded on PC2); Fresh fruit yield; and Number of seeds per fruit (loaded on PC4) were highly inter related.

Table 7 : Contribution of the parental chilli genotypes to the first three principal component axes under polyhouse environment.

Genotypes	PC1	PC2	PC3	PC4
King Chilli-A1	0.0002	18.6473	48.7826	2.9376
King Chilli-A5	0.2789	0.0047	4.9599	26.3843
King Chilli-A18	0.0273	0.2642	16.7808	11.9749
King Chilli-A19	0.3170	6.1568	4.3368	41.3286
King Chilli-A20	0.0798	17.4293	5.1830	1.1785
Krishna	8.4683	19.4552	0.0020	1.5226
Mem	20.5015	13.1684	5.5021	0.0083
Capsicum	57.8271	12.3740	1.9527	2.1652

The genotypes King chilli accessions A1, A5, A18, A19 and A20 projected on the vectors of Plant height, Number of Primary Branches, Days to 1st Flowering, Days to 50% Flowering, Hundred Seed Weight and Length of Fresh Fruit were close to them, indicating a positive correlation (Table 7). Then, the genotypes Krishna and Mem were superior for number of fruits per plant. Whereas, Capsicum was found to have a positive correlation with Fresh Fruit Weight, Girth of Fresh Fruit, Fresh Fruit Yield and Number of Seeds per Fruit. The genotypes with a high positive principal component score for PC1 were Capsicum (57.827), Mem (20.502), Krishna (8.468) and King chilli-A19 (0.317).

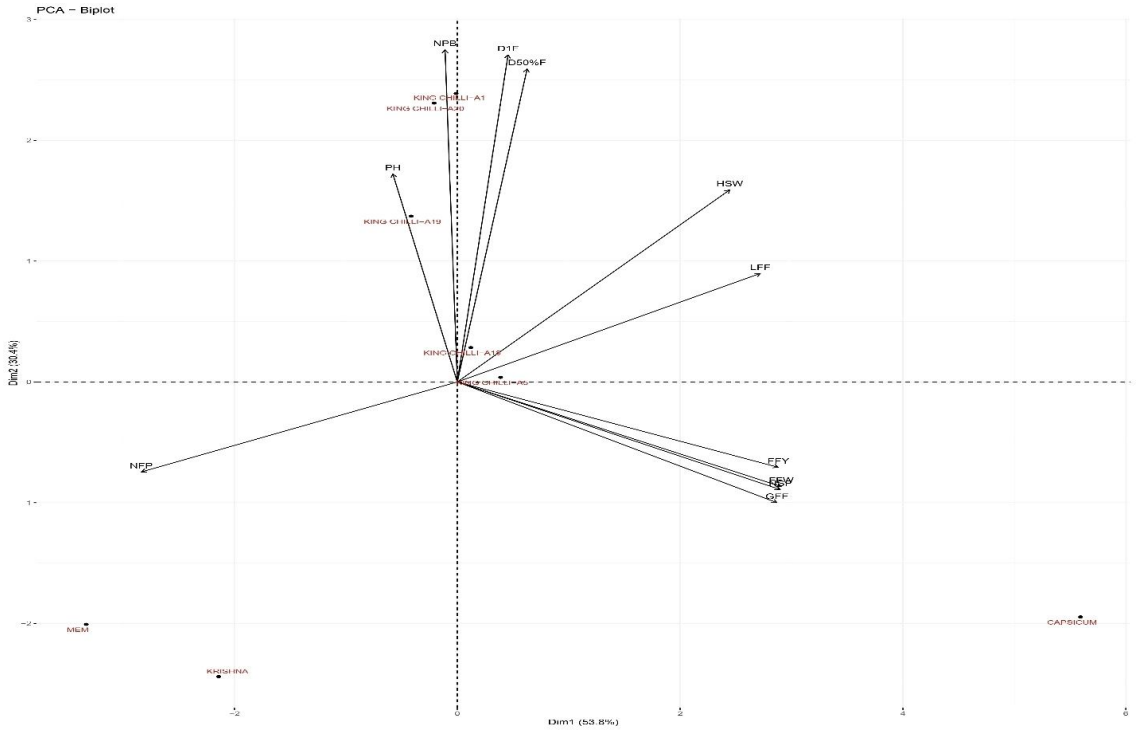

Fig. 5 : Distribution genotypes and traits across first two components based on PCA for polyhouse environment.

Table 8 : Analysis of mid-parent heterosis.

Genotypes	Capsicum x A18	Krishna x A18	A5 x MEM	MEM x A5
Plant height	-0.395	10.172	-9.882	35.937
Number of primary branches per plant	-33.333	-17.647	-25	-25
Number of secondary branches	-20	105.128	-45.455	-50
Number of nodes per plant	-47.453	32.007	51.544	-63.42
Number of leaves per plant	-42.867	162.847	59.147	-58.792
Length of leaf	-1.948	2.681	31.617	25.389
Breadth of leaf	-4.972	-9.41	20	24.419
Size of pollen	-30.958	-34.96	-19.435	-12.523
Pollen fertility	-7.369	-74.084	-47.872	-35.942
Days to first flowering	98.124	29.666	45.698	-17.017
Days to 50% flowering	68.112	31.611	36.905	-15.476
Number of fruits per node	-47.368	-47.368	-29.412	-5.882
Number of fruits per plant	-60.331	-79.121	-76.259	75.18
Length of fresh fruit (cm)	-62.223	-45.727	0.733	14.67
Length of dry fruit (cm)	-60.712	-47.78	32.136	39.677
Girth of fresh fruit (cm)	-61.062	-25.234	-0.262	-1.837
Girth of dry fruit (cm)	-63.371	-34.673	-43.182	-48.864
Fresh fruit weight (g)	-75.047	-62.094	25.778	-41.469
Dry fruit weight (g)	-80.153	-53.586	-5.128	-36.41
Number of seeds per fruit	-87.154	-92.228	-53.584	-25.597
100 seed weight (g)	-62.264	-23.729	-36.283	-39.823
Dry fruit yield per plant (g)	-90.579	-46.324	-1.296	22.143
Fresh fruit yield per plant (g)	-93.533	-85.572	-51.707	-0.048

Hence based on yield and yield attributing traits, these genotypes could be utilized in crop improvement programs of chilli to develop new high-yielding varieties of chilli. All the traits, except for the traits plant height, number of primary branches per plant and number of fruits per plant had positive contribution to PC1 in outdoor environment, which was not the case in the polyhouse environment. Therefore, an attempt was made to exploit heterosis by crossing among the genotypes belonging to three different *Capsicum* species in outdoor field conditions.

Study of mid-parent heterosis

In the current study, F_1 plants from four interspecific crosses (Capsicum × King chilli accession A18; Krishna × King chilli accession A18; King chilli accession A5 × Mem and Mem × King chilli accession A5) were studied for morphological characters to analyze mid-parent heterosis. From the study (Table 8), it was observed that, only the F_1 plants of the cross- Mem x King chilli-A5 showed a reduction in days to first and 50% flowering which are desirable for a breeding program. Number of fruits per plant (75.18) as well as size of the fruits were found to be increased which led to least reduction of Fresh fruit yield per plant (g) in case of Mem x King chilli-A5.

From these observations it can be assumed that Mem x King chilli-A5 was the most desirable F_1 hybrid in this study of interspecific hybridization. This also indicated the genetic closeness of Mem (*C. frutescens*) and King chilli (*C. chinense*) as discussed by Hazarika *et al.* (2023).

Conclusion

Most of the characters under study were found to have high heritability coupled with high genetic advance in percentage of mean. Number of fruits per plant had the highest heritability (96.58%) with 99.74 % GA. The trait also showed a positive contribution (0.380) to PC1 under polyhouse environment. Besides fresh fruit weight (0.365) was found to have highest positive contribution to PC1 under outdoor environment. Thus, these characters can be used for improvement of chilli through interspecific hybridization. It was found that days to first flowering, length and girth of fresh fruit, fresh and dry fruit weight, seeds per fruit, hundred seed weight and dry fruit yield per plant are positively correlated with fresh fruit yield per plant. This result can also help in selecting

direct and/or indirect traits for final yield improvement in chilli. The F_1 hybrid from the cross- Mem x King chilli-A5 was found to be the most desirable interspecific hybrid from the present study which can be further studied.

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Authors' contribution

All authors contributed substantially to the article's concept, analysis, data interpretation and drafting. GH conducted all the experiments with support from all authors. GH and RP critically revised the intellectual content of the draft. All authors finalized the version for submission.

Conflict of interest

The authors declare no competing interest.

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