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Elucidating the genetic variability and diversity among Chilli (*Capsicum annuum* L.) genotypes for growth and yield-related traits under sodic soil in Tamil Nadu through a multivariate approach

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Abstract

Chilli (*Capsicum annum* L.) is a commercially important crop cultivated for both vegetable and spice uses. This study aims to explore the genetic diversity of thirty genotypes under sodic soil conditions at HC&RI(W), Tiruchirappalli, over two seasons (Kharif and Rabi) in 2023-2024. Analysis of variance (ANOVA) revealed significant variability among the genotypes for thirteen different quantitative and qualitative parameters evaluated under sodicity. The phenotypic coefficient of variation was higher than the genotypic coefficient, suggesting minimal environmental influence on the traits. Most parameters exhibited high heritability, with several (e.g., number of days for first picking, seeds per pod and chlorophyll stability index) showing high genetic advance, indicating the potential for improvement through direct selection. Principal Component Analysis (PCA) reduced the genotypes to thirteen components, with the first four accounting for 73.24% of the variability. The genotypes are divided into five clusters based on the Euclidean distance through Mahalanobis D^2 analysis grouped the genotypes into five clusters, each cluster demonstrating superiority in specific traits suitable for further breeding. Notably, the high inter-cluster distance between clusters IV & V and III & V indicates diverse genetic material that could be valuable for hybridization programs aimed at improving sodic soil tolerance.

Keywords

Capsicum annum L.; genetic advance; heritability; sodicity

Introduction

Chilli (*Capsicum annum*) is a widely cultivated crop, primarily valued for its use as both a vegetable and spice. Known for its pungency due to the presence of capsaicin, chilli is an indispensable ingredient in Indian kitchens, with its fruits harvested both green and red. Beyond its culinary use, chilli contributes to various industries through the extraction of oleoresin, which is used in food processing and pharmaceuticals. Dry chillies are used to prepare various food products such as curry powder and curry paste, and in the preparation of soups, sauces, pickles, salads etc. Globally, the Capsicum genus includes more than 38 species, with Capsicum annum being one of the most commercially important and originated from Latin America (1). Originally introduced to India by the Portuguese in the 17th century, chilli is now cultivated across major states like Tamil Nadu, Karnataka, Andhra Pradesh, Orissa, Maharashtra, West Bengal, Madhya Pradesh and Rajasthan, accounting for over 80% of the country's total production.

Chilli thrives in tropical and sub-tropical regions with optimal temperature ranging between 15°C to 30°C and in well-drained clay loam with a pH of around 6.5. Sodicity is the abiotic stress that hinders the crop growth and productivity due to the high proportion of sodium ions in the soil. Sodicity occurs as the sodium ions get leached and bind with the clay particle displacing other cations (2). Sodicity disrupts soil structure, hindering plant growth and productivity by limiting nutrient uptake. In India, about 6.73 million hectares of land are affected by salinity, with 2.96 million hectares specifically affected by sodic soils. Chilli is particularly sensitive to these conditions, making it essential to explore genotypic variations that may help improve tolerance.

This study aims to evaluate the performance of 30 chilli genotypes under sodic soil conditions to identify those with superior growth, yield, and quality. By assessing genetic variability and heritability, the research seeks to provide insights that will inform future breeding programs designed to improve chilli tolerance to sodicity and enhance overall productivity.

Materials and Methods

The experiment was conducted at the Department of Vegetable Science, HC&RI(W), Tiruchirappalli during 2023-2024 for two seasons. The site is geographically located at 85 m above mean sea level with coordinates of 10°75'' latitude and 78°60'' longitude. The average mean temperature ranges about 32.76°C with an annual rainfall of 815 mm. Soil samples were randomly collected from four different places across the experimental area and bulked for analysis of pH, electrical conductivity, and exchangeable sodium percentage. Soil type prevailing was sodic with pH of 9.10, electrical conductivity of 2.21 dSm^{-1} and exchangeable sodium percentage of 18.3% throughout the experimental area. Soil is ploughed three to four times to obtain a fine tilt where about farmyard manure (25 tons/hectare) was applied to soil before the last plough. About 30 genotypes of chilli were evaluated which were obtained from National Bureau of Plant Genetic Resources, Indian Council of Agriculture Research, New Delhi and Ramaiah Gene Bank, Department of Plant Genetic Resources, TNAU, Coimbatore. The experiment was carried out under Randomised Block Design where each genotype was replicated thrice. The seeds were raised under the portray and initially kept under mist chamber for five days; later transferred to shade net. Transplanting was done to main field at 30 days after sowing (DAS) *viz*., July'23 for the first season (Kharif) and November'23 for the second season (Rabi). Irrigation and nutrient application were stopped a day before transplanting to main field. The spacing adapted for the crop production was 60 cm × 45 cm. About 30 plants were maintained for each genotype and raised under ridges and furrow system of crop production. The plants were irrigated two days once and about 30 kg/ha of nitrogen was given as top dressing in three equal splits *viz*., 30, 60 and 90 days after planting.

Various parameters *viz*., Plant height, Leaf area, Days for first flowering, Days for 50% flowering, Fresh weight, Dry weight, Number of days for first picking, Number of seeds per pod, Pod length, Pod diameter, Proline content, Chlorophyll Stability Index, Total chlorophyll content were observed in all the thirty genotypes for the two seasons. The parameters of plant height and leaf area were measured using meter scale while the leaf area was measured at 30 cm above the ground level. The fresh weight of the fruits was measured using the standard weighing balance. The pods were allowed to dry in the shade and so the dry weight was obtained. The pod quality parameters *viz*., pod length and pod diameter were measured using meter scale and vernier callipers.

Estimation of proline

The proline content (µg/g) in the leaves was estimated through the Acid Ninhydrin method (3). About 0.5 g of sample was homogenized with 3% sulphosalicylic acid and centrifuged for about 10 min at 1000 rpm at 4°C to avoid degradation. The supernatant was extracted and added with 2mL of acid ninhydrin and glacial acetic acid. The sample was incubated in water bath for about one hour and 4 mL of toluene was added. Chromopore containing the toluene was transferred and absorbance was observed at 520 nm. A standard curve was constructed using a known concentration of proline to calculate the content present in leaf samples. The standard proline solution was used for zeroing the spectrophotometer.

$$\text{Proline } (\mu g/g) = \frac{\mu g \text{ of proline/ml} \times 4}{115.50} \times 10$$

.....(Eqn. 1)

Estimation of total chlorophyll and chlorophyll stability index

The total chlorophyll content (mg/g) was estimated at the vegetative stage of 45 days after transplanting through acetone method (4). The samples were homogenized with

80% acetone and centrifuged at 3000 rpm for 10 min. The absorbance was observed at 652 nm in spectrophotometer.

$$\text{Total Chlorophyll content (mg/g)} = \frac{\text{OD@652 nm} \times V}{34.5 \times W}$$

…….(Eqn. 2)

Where V – Volume of acetone made and W-weight of the leaf sample

The chlorophyll stability index in the leaves was calculated to estimate the relationship between the total chlorophyll content under stress and control at the vegetative stage of 45 days after transplanting (5).

$$\text{CSI (\%)} = \frac{\text{Total Chlorophyll under stress}}{\text{Total Chlorophyll under control}} \times 100$$

…….(Eqn. 3)

Genetic parameters

Various genetic parameters *viz*., genotypic variance, phenotypic variance, environmental variance, genotypic coefficient of variance (GCV), phenotypic coefficient of variance (PCV), environmental coefficient of variance, genetic advance as percentage of mean and heritability were computed for all the traits among thirty genotypes. The parameters are estimated with the recorded observations through R studio software (version 4.4.1).

Statistical analysis

The observations obtained from two seasons were pooled and the pooled mean data was subjected to statistical analysis at 5% level of significance using SPSS (version 23). The phenotypic diversity among the thirty genotypes for all the recorded traits were analyzed by Mahalanobsis D^2 analysis computed through TNAUSTAT statistical package (6). Meanwhile principal component analysis was also computed using the R studio software package *viz.,* FactoMineR and factoextra (version 4.4.1). The number of principal components were selected based on the eigen values that ranged more than one.

Results

Growth and yield traits

The diversity of thirty genotypes in chilli exhibited significant variation for all the growth, yield and quality related traits (Table 1). The range, mean, variance, coefficient of variance, heritability and genetic advance as percent of mean were depicted in Table 2. The plant height ranged between 40.50 cm to 73.80 cm while the leaf area ranged between 6.36 cm^2 to 37.44 cm^2. The genotype IC255943 performed superior in terms of earliness traits *viz.,* days for first flowering (10.78), days for fifty percent flowering (18.23), number of days for first picking (59.44). The yield parameters *viz.,* yield per plant ranged between 4.08 kg to 7.11 kg while the dry yield per plant ranged between

Table 1. Pooled data for growth, yield and quality related traits among thirty chilli genotypes under sodic soil

	PH	LA	DFFF	DFPF	YPP	DYPP	NDFP	NSP	PL	PD	PC	CSI	TC
EC599981	69.35	10.54	24.12	29.26	5.67	1.32	68.23	70.12	7.86	6.21	300.12	80.56	1.23
EC599977	58.30	9.18	25.23	28.02	5.93	2.63	66.43	61.43	6.70	5.06	321.44	79.89	1.05
IC255913	60.11	10.47	22.63	29.33	5.87	2.41	69.21	63.22	6.68	5.57	275.11	73.11	0.99
IC255926	69.45	15.17	26.45	31.54	5.25	1.54	71.15	58.52	7.05	5.11	238.12	73.35	1.01
IC255927	42.30	12.54	25.13	31.67	5.61	2.30	67.25	61.31	5.65	4.79	248.91	79.72	1.12
IC255941	40.50	11.23	24.12	30.32	6.85	2.58	70.54	59.16	5.87	4.87	325.67	85.23	1.32
IC255943	58.10	10.73	10.78	18.23	6.41	1.70	59.44	68.62	8.58	6.54	312.66	84.12	1.35
IC255944	65.20	8.57	23.56	29.98	6.02	1.45	75.23	59.54	6.87	5.73	260.12	75.23	1.01
IC208534	67.50	15.91	24.24	28.74	4.52	0.89	73.12	73.35	8.60	5.90	246.89	75.78	0.98
IC208580	60.13	16.88	20.11	18.38	6.34	1.49	67.75	74.12	8.97	6.72	325.10	86.95	0.93
IC208591	72.40	6.44	26.41	32.43	4.98	1.28	74.42	53.64	7.18	4.13	301.90	80.23	0.87
IC545721	50.53	17.99	22.90	28.12	6.09	1.39	70.05	56.68	6.49	4.58	267.45	74.01	0.79
IC545722	54.41	10.98	24.67	28.67	5.07	1.38	68.23	59.81	6.01	4.08	237.89	73.85	0.80
IC545723	52.20	9.57	23.45	27.51	5.10	1.30	66.11	55.72	5.65	4.74	330.12	79.33	0.71
IC545732	56.34	10.17	17.35	22.90	5.86	1.47	69.37	69.95	7.39	6.14	356.78	80.87	0.79
TNAUH00400011	67.40	7.89	25.21	29.82	4.21	0.93	73.21	57.78	6.77	4.18	311.82	83.67	0.98
TNAUH00400012	40.57	15.85	23.42	26.12	6.75	2.34	70.17	71.65	7.01	6.89	289.12	73.99	0.80
TNAUH00400015	62.60	6.36	16.55	20.68	6.18	1.78	62.78	68.49	7.43	5.96	240.78	76.23	0.83
TNAUH00400018	58.34	9.33	17.32	22.42	6.45	2.09	64.63	74.32	7.81	6.02	280.11	74.12	0.81
TNAUH00400028	42.36	10.04	26.11	32.81	4.97	0.91	73.45	58.56	7.58	5.16	290.11	83.56	1.16
TNAUH00400034	69.12	9.08	24.04	30.74	7.11	1.67	74.37	56.56	6.46	5.00	312.54	82.30	1.08
TNAUH00400035	43.54	9.41	25.65	31.43	6.87	1.43	69.23	67.03	6.82	5.72	302.83	80.12	1.10
TNAUH00400037	62.30	16.18	24.38	29.37	5.10	1.11	67.45	66.45	5.13	4.79	338.65	84.67	1.14

TNAUH00400039	58.75	15.49	25.71	30.62	4.36	1.08	71.52	57.56	7.89	4.34	304.56	76.38	0.95
TNAUH00400042	73.80	15.52	26.22	32.75	4.08	1.09	69.21	63.74	6.66	4.78	245.78	71.23	0.79
TNAUH00400048	68.50	18.91	20.34	25.32	5.12	1.71	65.06	66.32	6.74	5.68	278.91	72.67	0.83
TNAUH00400084	68.80	6.85	24.70	30.29	5.47	1.76	72.28	61.19	5.89	4.87	295.67	84.92	0.92
TNAUH00400088	53.12	6.75	20.82	27.34	5.06	1.55	64.60	68.28	6.82	6.11	346.67	83.61	0.90
TNAUH00400103	69.70	21.15	28.47	33.08	5.85	1.41	73.55	64.89	6.36	4.56	228.67	70.56	0.68
TNAUH00400112	71.3	37.44	24.62	29.72	6.63	1.49	66.45	69.02	5.93	4.23	257.89	79.02	0.72
SE(m)	0.84	0.30	0.35	0.42	0.08	0.03	1.10	1.05	0.11	0.08	4.68	1.31	0.02
CD (0.05%)	2.38	0.85	1.01	1.20	0.24	0.08	3.11	2.98	0.32	0.24	13.26	3.70	0.05

PH- Plant height; **LA**-Leaf area; **DFFF**-Days for first flowering; **DFPF**-Days for fifty percent flowering; **YPP**-Yield per plant; **DYPP**-Dry yield per plant; **NDFP**-Number of days for first picking; **NSP**-Number of seeds per pod; **PL**-Pod length; **PD**-Pod diameter; **PC**-Proline content; **CSI**- Chlorophyll stability index; **TC**-Total chlorophyll content; **SE(m)**-Standard error of mean; **CD**-Critical difference.

Table 2. Genetic Variability for the pooled estimates among thirty chilli genotypes under sodic soil

Characters	Minimum	Maximum	Mean	SS	EV	GV	PV	ECV	GCV	PCV	Heritability	GAM (%)
PH	40.50	73.80	59.56	9079.70	2.13	103.56	105.78	2.45	17.09	17.26	0.98	34.85
LA	6.36	37.44	12.75	3301.70	0.27	37.86	38.13	4.09	48.24	48.42	0.99	99.02
DFFF	10.78	28.47	23.15	1178.95	0.38	13.42	13.80	2.67	15.82	16.04	0.97	32.14
DFPF	18.23	33.08	28.25	1435.55	0.54	16.32	16.86	2.60	14.29	14.53	0.96	28.97
YPP	4.08	7.11	5.65	59.69	0.02	0.67	0.70	2.57	14.56	14.78	0.97	29.54
DYPP	0.89	2.63	1.58	20.19	0.00	0.23	0.23	2.99	30.39	30.53	0.99	62.31
NDFP	59.44	75.23	69.14	1236.44	3.62	13.00	16.62	2.75	5.21	5.89	0.78	9.50
NSP	53.64	74.32	63.90	3125.11	3.33	34.81	38.14	2.86	9.23	9.66	0.91	18.17
PL	5.13	8.97	6.89	74.25	0.04	0.84	0.88	2.84	13.30	13.60	0.95	26.78
PD	4.08	6.89	5.28	57.23	0.02	0.65	0.67	2.79	15.27	15.52	0.97	30.94
PC	228.67	356.78	289.08	111703.00	65.88	1261.98	1327.86	2.80	12.28	12.60	0.95	24.68
CSI	70.56	86.95	78.64	1962.61	5.14	20.85	25.98	2.88	5.80	6.48	0.80	10.71
TC	0.68	1.35	0.95	2.72	0.00	0.03	0.03	2.89	18.44	18.68	0.97	37.51

PH- Plant height; **LA**-Leaf area; **DFFF**-Days for first flowering; **DFPF**-Days for fifty percent flowering; **YPP**-Yield per plant; **DYPP**-Dry yield per plant; **NDFP**-Number of days for first picking; **NSP**-Number of seeds per pod; **PL**-Pod length; **PD**-Pod diameter; **PC**-Proline content; **CSI**- Chlorophyll stability index; **TC**-Total chlorophyll content; **EV**-Environmental variance; **GV**-Genotypic variance; **PV**-Phenotypic variance; **GCV**- Genotypic coefficient of variance; **PCV**- Phenotypic coefficient of variance; **GAM**- Genetic advance as percent of mean.

0.89 kg to 2.63 kg. The parameters on pod quality *viz.,* number of seeds per pod (74.32) recorded maximum in TNAUH00400018, pod length (8.97 cm) in IC208580 and pod diameter (6.89 cm) in TNAUH00400012.

Proline and chlorophyll content

The genotype IC545732 (356.78 µg/g) observed the maximum proline content followed by TNAUH00400088 (346.67 µg/g) while chlorophyll stability index observed maximum in IC208580 (86.95%) followed by IC255941 (85.23%). On the contrary, genotype TNAUH00400103 was recorded for the minimum proline content (228.67 µg/g), chlorophyll stability index (70.56%) and total chlorophyll content (0.68 mg/g). The total chlorophyll content ranged from 0.68 mg/g to 1.35 mg/g with the mean around 0.95 mg/g.

Genetic diversity

GCV and PCV are the plant breeding tools that help in understanding the variability among the genotypes. GCV depicts the amount of variability that could be passed to the next generation while the PCV depicts both heritable and non-heritable variability in the phenotype. The level of GCV ranged between 5.21% to 48.24% where the traits *viz.,* leaf area (48.24%), dry yield per plant (30.39%), total chlorophyll content (18.44%), plant height (17. 09%), days for first flowering (15.82%), pod diameter (15.27%) recorded the highest GCV of more than 15% while yield per plant (14.56%), days for fifty percent flowering (14.29%), pod length (13.30%) and proline content (12.28%) recorded for the moderate GCV of 10% -15%. The level of PCV ranged from 5.89% for number of days for first picking to 48.42% for leaf area. Heritability observed maximum of more than 75% for all traits ranging from 78% (number of days for first picking) to 99% (leaf area and dry yield per plant) whereas the genetic advance as percentage of mean ranged from 9.50% (number of days for first picking) to 99.02% (leaf area).

Principal Component Analysis

The pooled season data obtained from two seasons *viz.,* kharif and rabi during 2023-2024 among thirty genotypes were used for PCA analysis. In general, PCA reduces the large dimensional data into smaller ones capturing most of the variations. The data obtained were divided into twelve principal components and the first component alone showed the maximum magnitude of variation (33.24%) (Table 3). The first four components recorded

Table 3. Thirteen principal components for growth, yield and quality traits among the thirty chilli genotypes under sodic soil

Particulars	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13
Eigen value	4.32	2.37	1.75	1.07	0.96	0.68	0.64	0.45	0.28	0.20	0.12	0.08	0.05
Variability	33.24	18.26	13.50	8.24	7.38	5.26	4.96	3.48	2.17	1.52	0.97	0.64	0.37
Cumulative	33.24	51.51	65.00	73.24	80.62	85.89	90.85	94.32	96.49	98.01	98.98	99.63	100.00
PH	-0.14	0.30	-0.33	-0.12	0.10	-0.72	-0.38	0.27	0.00	0.08	0.06	-0.08	0.01
LA	-0.09	0.36	0.20	-0.26	0.66	0.04	0.22	-0.19	-0.35	0.16	-0.25	-0.13	-0.09
DFFF	-0.42	-0.09	0.07	0.18	0.24	0.18	0.00	0.29	-0.14	-0.21	0.40	-0.35	0.51
DFPF	-0.43	-0.15	0.08	0.19	0.14	0.02	0.12	0.26	0.08	0.21	0.28	0.12	-0.71
FW	0.24	-0.07	0.46	0.17	0.33	-0.17	-0.39	-0.37	0.32	0.13	0.39	0.05	0.06
DW	0.18	-0.12	0.58	0.14	-0.16	-0.24	-0.15	0.31	-0.54	-0.26	-0.16	0.03	-0.13
NDFP	-0.33	-0.12	-0.14	0.45	0.21	0.14	-0.45	-0.12	0.00	-0.06	-0.55	0.23	0.05
NSP	0.33	0.30	-0.03	0.06	0.33	0.18	0.08	0.51	0.24	-0.25	0.04	0.51	0.08
PL	0.25	0.17	-0.43	0.43	0.05	0.03	0.02	-0.31	-0.50	-0.16	0.37	0.07	-0.16
PD	0.41	0.09	-0.07	0.35	0.05	0.18	-0.08	0.30	0.14	0.30	-0.19	-0.64	-0.14
PC	0.19	-0.42	-0.19	-0.35	0.13	0.25	-0.34	0.20	-0.35	0.46	0.13	0.19	0.09
CSI	0.15	-0.47	-0.22	-0.26	0.35	-0.07	-0.05	-0.04	0.13	-0.59	-0.06	-0.25	-0.28
TC	0.12	-0.43	-0.09	0.31	0.21	-0.45	0.53	0.03	0.00	0.25	-0.13	0.13	0.27

PH- Plant height; **LA**-Leaf area; **DFFF**-Days for first flowering; **DFPF**-Days for fifty percent flowering; **YPP**-Yield per plant; **DYPP**-Dry yield per plant; **NDFP**-Number of days for first picking; **NSP**-Number of seeds per pod; **PL**-Pod length; **PD**-Pod diameter; **PC**-Proline content; **CSI**- Chlorophyll stability index; **TC**-Total chlorophyll content; **PC**- Principal component.

eigen value more than one and accounted for 73.24% of cumulative variability out of 100% while the other nine components recorded for the eigen value of less than one and accounted for the minimum amount of variability as illustrated in scree plot (Fig. 1). The components that exhibited eigen value less than one could be ignored as they could only provide minor variations which have no practical significance in the breeding programs. These minor variations could also distract from the primary breeding goals. In order to achieve targeted breeding goals, the variations associated with the first four components that have eigen value more than one alone were selected. The PC1 has the positive loading for all the traits (0.12-0.41) studied except for the plant height (-0.14), leaf area (-0.09), days for first flowering (-0.42), days for fifty percent flowering (-0.43) and number of days for first picking (-0.33). The PC2 recorded negative loading for days for first flowering (-0.09), days for fifty percent flowering (-0.15), fresh weight (-0.07), dry weight (-0.12), number of days for first picking (-0.12), proline content (-0.42), CSI (-0.47) and total chlorophyll content (-0.43) while positive loading was recorded for plant height, leaf area, number of seeds per pod, pod length and pod diameter ranging from 0.09-0.36.

The PCA biplot (Fig. 2) between PC1 and PC2 was constructed to graphically illustrate the diversity and variation among the different genotypes. The genotypes TNAUH00400012, TNAUH00400015, TNAUH00400018 and IC208580 in quadrant 4 exhibited higher values for the pod quality traits *viz.,* pod length, pod diameter and number of seeds per pod. The yield parameters *viz.,* yield per plant and dry yield per plant; proline content, CSI, and total chlorophyll content grouped in quadrant 2 exhibited highest in the genotypes IC545732 and TNAUH00400088. Genotypes *viz.,* IC208591, TNAUH00400011, TNAUH00400084 and TNAUH00400028 were placed in quadrant 1 with maximum number of days for first flowering and days for fifty

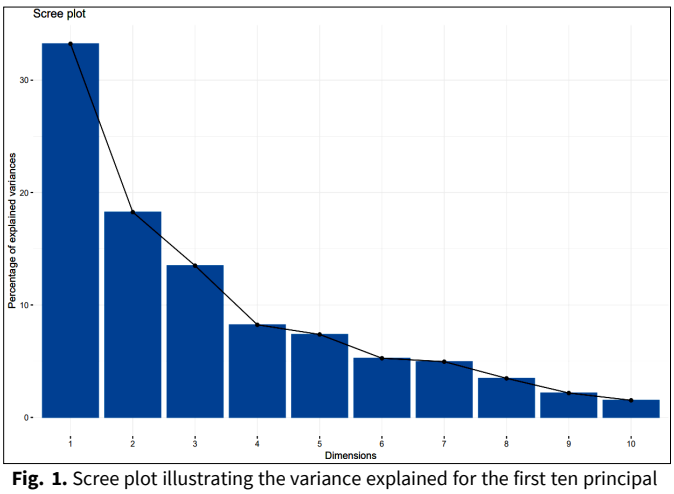

Fig. 1. Scree plot illustrating the variance explained for the first ten principal components.

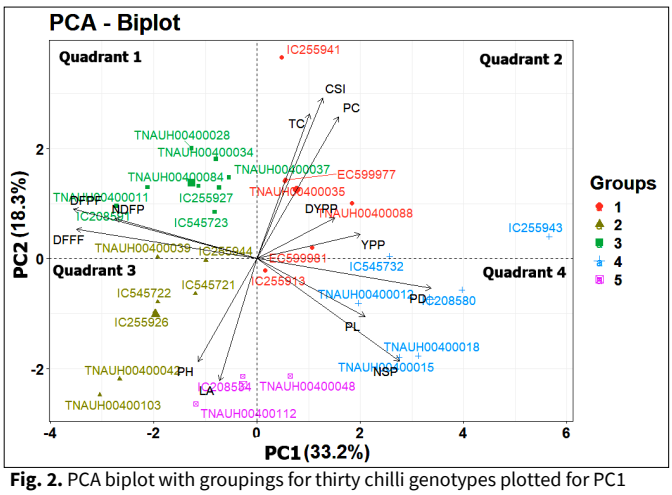

Fig. 2. PCA biplot with groupings for thirty chilli genotypes plotted for PC1 and PC2 components.

percent flowering while the genotype IC208534 for maximum plant height and leaf area was placed in quadrant 3. The genotypes *viz*., IC255941 TNAUH00400103 TNAUH00400042 were highly diverse from the other genotypes.

Further, the genotypes were clustered into five groups based on the superiority of the genotypes for the particular trait. The grouping of genotypes under the PCA biplot revealed that the genotypes in groups 2 and 5 exhibited high plant height and leaf area with low total chlorophyll content, chlorophyll stability index and proline content. The genotypes in group 1 reported the high proline content along with the high yield characters *viz.,* yield per plant and dry yield per plant. This indicates the direct relation between the yield per plant and proline content. Some of the genotypes under group 3 *viz.,* IC208591 & TNAUH00400011 and group 2 *viz.,* TNAUH00400039 showed the superiority for the characters on earliness *viz.,* days for first flowering, days for fifty percent flowering and number of days for first picking with poor pod characters. The genotypes exhibiting the superior pod characters with better yield per plant were placed in group 4.

The trait association reveals that the number of days for first flowering has a close association with the number of days for fifty percent flowering and the number of days for first picking. Plant height and leaf area exhibited a positive association while they exhibited a negative association with the fresh weight, dry weight, proline content, CSI, and total chlorophyll content (Fig. 3).

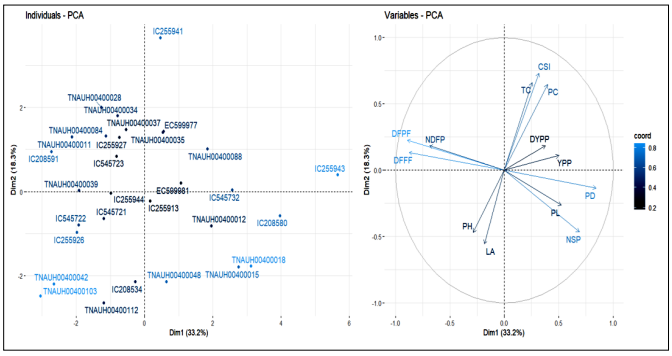

Fig. 3. Association of thirty chilli genotypes and various growth, yield, quality related parameters owing to the PC1 and PC2 principal component.

Mahalanobis D2 Cluster analysis

The phenotypic distance matrix was constructed among the thirty chilli genotypes for all thirteen characters. The genotypes were classified into five clusters according to tocher clustering technique with the cut off value of 1531.36 (Table 4). The cluster I comprised 25 genotypes and considered as largest cluster followed by cluster II (IC208534, TNAUH00400103) consisting of two genotypes whereas the cluster III (TNAUH00400028), cluster IV (IC255943) and cluster V (TNAUH00400112) comprised of only one genotype at each cluster. The contribution of each trait to the clusters revealed that the dry yield per plant (28.05%) and leaf area (23.22%) contributed more to the formation of clusters while the number of days for first picking, number of seeds per pod and proline content exhibited nil contribution to the clusters (Fig. 4). There exists a considerable genetic difference among the clusters based on the cluster mean of different genotypes (Table 5).

Table 4. Cluster formation among thirty chilli genotypes evaluated under sodic soil based on Mahalanobis D^2 analysis

Cluster	Number of Genotypes	Name of Genotypes
I	25	EC599981, EC599977, IC255913, IC255926, IC255927, IC255941, IC255944, IC208580, IC208591, IC545721, IC545722, IC545723, IC545732, TNAUH00400011, TNAUH00400012, TNAUH00400015, TNAUH00400018, TNAUH00400034, TNAUH00400035, TNAUH00400037, TNAUH00400039, TNAUH00400042, TNAUH00400048, TNAUH00400084, TNAUH00400088
II	2	IC208534, TNAUH00400103
III	1	TNAUH00400028
IV	1	IC255943
V	1	TNAUH00400112

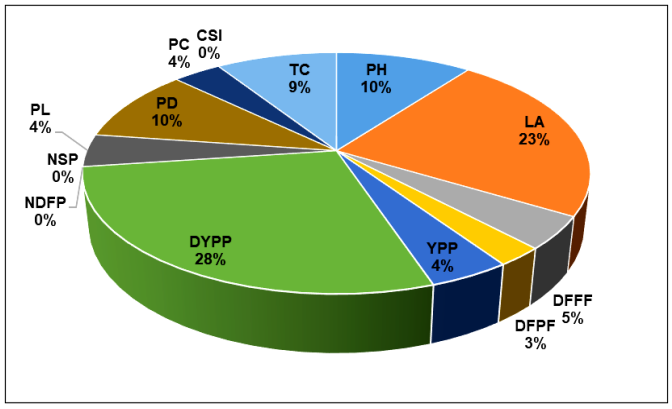

Fig. 4. Contribution of various parameters in cluster formation through Mahalanobis D^2 analysis.

The highest cluster mean was recorded for plant height (71.30), leaf area (37.45), yield per plant (6.63) in cluster V; days for first flowering (26.36) and number of seeds per pod (69.12) in cluster II; days for fifty percent flowering (32.81), number of days for first picking (73.45) in cluster III; dry yield per plant (1.70), pod length (8.58), pod diameter (6.54), proline content (312.66), chlorophyll stability index (84.12) and total chlorophyll content (1.35) in cluster IV.

The Cluster distance helps in understanding the distinctiveness and quality of the clusters. Intra-cluster distance shows how close the genotypes are grouped in the cluster while inter-cluster distance shows how far the clusters are arranged for the genotypes. Higher inter-cluster distance indicates that the genotypes present in the different clusters differ in their characteristics in terms of growth, yield and quality. Inter-cluster and intra-cluster distance depicted in Table 6 showed that the highest intra-cluster distance was recorded in cluster I (952.65) followed by cluster II (910.75) while the clusters III, IV and V remains solitary as there exist no intra-cluster distance. The inter-cluster distance recorded maximum between cluster IV and cluster V (5180.76) followed by cluster III and V (4771.81), cluster I and V (3940.62), cluster II and IV (2873.49), cluster III and IV (2307.97), cluster II and V (2298.39) whereas minimum between cluster I and III (1235.93) followed by cluster I and II (1279.95), cluster I and IV (1910.22).

Table 5. Cluster mean obtained through Mahalanobsis D^2 analysis for different growth, yield and quality traits among thirty chilli genotypes

Cluster	PH	LA	DFFF	DFPF	YPP	DYPP	NDFP	NSP	PL	PD	PC	CSI	TC
I	59.12	11.49	23.22	28.20	5.66	1.64	69.14	63.30	6.79	5.28	293.45	78.65	0.95
II	68.60	18.53	26.36	30.91	5.19	1.15	73.34	69.12	7.48	5.23	237.78	73.17	0.83
III	42.36	10.04	26.11	32.81	4.97	0.91	73.45	58.56	7.58	5.16	290.11	83.56	1.16
IV	58.10	10.73	10.78	18.23	6.41	1.70	59.44	68.62	8.58	6.54	312.66	84.12	1.35
V	71.30	37.45	24.62	29.72	6.63	1.49	66.45	69.02	5.93	4.23	257.89	79.02	0.72

PH- Plant height; **LA**-Leaf area; **DFFF**-Days for first flowering; **DFPF**-Days for fifty percent flowering; **YPP**-Yield per plant; **DYPP**-Dry yield per plant; **NDFP**-Number of days for first picking; **NSP**-Number of seeds per pod; **PL**-Pod length; **PD**-Pod diameter; **PC**-Proline content; **CSI**- Chlorophyll stability index; **TC**-Total chlorophyll content.

Table 6. Intra cluster and Inter cluster distance obtained through Mahalanobsis D^2 analysis among the five clusters obtained from thirty chilli genotypes for different growth, yield and quality traits

	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster V
Cluster I	952.65	1279.95	1235.93	1910.22	3940.62
Cluster II	-	910.75	1307.69	2873.49	2298.39
Cluster III	-	-	0	2307.97	4771.81
Cluster IV	-	-	-	0	5180.76
Cluster V	-	-	-	-	0

Discussion

The present study examines the divergence among the thirty chilli genotypes for different growth, yield and quality parameters under the sodic soil. The pooled data obtained from the two seasons *viz*., kharif and rabi during 2023-2024 were subjected to statistical analysis. The genotype IC255943 was considered better in terms of earliness and so the genotype could be considered in future hybridization programs in the development of hybrid with earlier traits.

The traits of leaf area and dry yield per plant exhibited the highest PCV and GCV. This shows the greater amount of variability present in the traits and further depicts the significance of the traits in the breeding programs (7). The previous findings also suggest the presence of variability in chilli for the yield parameters (8–10). The present study observed that the PCV is greater than the GCV for all the traits and infers that there exists only a little amount of environmental influence on the studied traits. Low PCV and low GCV were observed for the number of days for first picking and number of seeds per pod indicating no variability among the above traits whereas the low GCV coupled with moderate PCV noticed for chlorophyll stability index indicates the influence of environment among the traits. Moderate PCV and moderate GCV exhibited in plant height, days for first flowering, days for fifty percent flowering, yield per plant, pod length, pod diameter, proline content and total chlorophyll content. The previous findings in chilli under a hot ecosystem suggest that there exists high PCV and GCV for the yield-related traits (11). Most of the traits in the present study exhibit only a slight difference between the PCV and GCV which indicates a little amount of environmental influence on the traits.

Heritability determines the proportion of total variation among the population due to the genetic differences between the genotypes. The broad sense heritability observed highest for most of the traits in the present study ranging from 78% to 99% with eleven out of thirteen characters ranged more than 90% for their heritability (12). Selection of superior individuals for the further breeding was computed through heritability and genetic advance in combination. The traits of plant height, leaf area, days of first flowering, days for fifty percent flowering, yield per plant, dry yield per plant, pod length, pod diameter, proline content and total chlorophyll content observed for the high heritability coupled with high genetic advance as a percentage of mean, while number of seeds per pod and chlorophyll stability index observed for the high heritability coupled with moderate genetic advance as a percentage of mean. The previous findings in chilli also recorded high heritability with high genetic advance for number of pods per plant, yield per plant, dry yield per plant, pod length and pod weight (13). High heritability coupled with high genetic advance indicates that the traits were governed by the additive gene action. This provides ample scope for improving the trait through phenotypic selection (14). Thus, the selection of superior genotypes from the population could be highly beneficial in the improvement of the trait. Similarly high heritability coupled with moderate genetic advance as percentage of mean provides the need for the individual plant selection in improvement of genotypes. Correspondingly high heritability coupled with low genetic advance was observed in number of days for first picking indicating that the above traits are governed by the non-additive gene action. The findings confirm that the selection will not be beneficial in the improvement of genotypes where the heterosis would be beneficial in their improvement (15).

Principal Component Analysis is a dimension reduction method that reduces the multivariate large set of data into small components that contribute maximum variability (16). Here in the present study, four principal components alone contribute to the 73.24% variability for the thirteen characters. The genotypes strewed into four different quadrants *viz.,* 1,2,3 and 4 that exhibit the high genetic variability for all the traits. The PCA biplot obtained from the present study reveals that the plant height is closely related to leaf area. Similarly, the number of days for first flowering also exhibits close relation with the number of days for fifty percent flowering and number of days for first picking. Increased pod length and pod diameter facilitated the increase in the number of seeds per pod. The parameters *viz*., proline content, chlorophyll stability index and total chlorophyll content were closely associated

with the yield paramters *viz*., yield per plant and dry yield per plant.

The grouping of genotypes under the PCA biplot also revealed that the genotypes in group 1 exhibiting high proline content also exhibited better yield-related traits *viz.,* yield per plant and dry yield per plant. This might be due to the sodicity factor where more amount of antioxidants were produced. Sodicity is one of the abiotic stresses caused due to the accumulation of sodium ions than the other cations (17). During stress, reactive oxygen species (ROS) accumulate and cause oxidative stress. As the stress progresses the ROS accumulates at the higher levels and disturbs the routine cellular metabolism (18). Further, proline accumulates in the plants and acts as a metal chelator, osmolyte, signaling molecule and antioxidant to cope with the stress (19). Proline also stabilizes the cellular membrane and maintains the osmotic balance providing stress tolerance to plants (20). The genotypes with high proline content and chlorophyll stability index effectively performed under the stress conditions and paved for the increased yield since the proline content and chlorophyll stability index are considered sodicity screening traits. Proline content in the plants directly correlates with the plant yield as the proline imparts stress tolerance and so the plants are able to provide good yield (21). Five out of six genotypes exhibited better pod characters along with better yield-related traits.

Mahalanobis D^2 cluster analysis revealed that the genotypes were divided into five clusters based on their genetic divergence. Cluster I comprised a maximum of 25 genotypes as they were closely related to each other. The cluster III, IV and V comprised only of one genotype each which exposed the uniqueness of genotypes for the studied characters. The maximum genetic distance was found between the cluster IV and V (5180.76) followed by cluster III and V (4771.81). The previous reports also reiterated the existence of maximum inter-cluster distance (22). The presence of single genotype IC255943 in cluster IV and TNAUH00400112 in cluster V with maximum genetic distance between them affirmed they are highly divergent and could be used as parents for the further hybridization programs. The genotype TNAUH00400112 in cluster V as one of the parents could be crossed with either TNAUH00400028 in cluster III or any of the genotypes in cluster I paves for exploiting the maximum heterosis due to the maximum genetic distance obtained between the above clusters. The lowest intra-cluster distance between cluster I and III (1235.93), cluster I and cluster II (1279.95), cluster I and IV (1910.22) disclosed that there exists only a little amount of divergence among the above inter-clusters.

The highest cluster mean obtained from cluster V for plant height, leaf area, and yield per plant revealed that the genotypes present in the cluster V (TNAUH00400112) could be exploited in plant breeding programs to enhance the above characters *viz*., plant height, leaf area, yield per plant. Similarly, the dry yield per plant, pod length, pod diameter, proline content, chlorophyll stability index and total chlorophyll content could be enhanced by selecting the genotype from cluster IV (IC255943) as the cluster mean recorded highest for the above traits in the respective cluster. The clustering obtained from the PCA biplot was just about similar to that of cluster obtained from Mahalanobis D^2 analysis such that in both the mode of clustering, the genotypes were grouped into five clusters. Group 5 from PCA biplot and cluster II from D^2 analysis similarly exerted influence on the growth parameters. The genotypes that comes for flowering and picking earlier along with better yield-related parameters were placed in cluster I through D^2 analysis and comparatively placed under groups 1 and 3 through PCA biplot analysis.

Conclusion

The present study concluded that there exists a significant amount of variability among the thirty genotypes for its growth, yield and quality. The traits of growth, earliness, yield and quality were associated with its high heritability coupled with high genetic advance. The traits were governed by additive gene action where the superior genotypes could be identified through the simple selection. The PCA biplot concluded that genotypes IC545732 and TNAUH00400088 were observed for the higher yield, proline content, chlorophyll stability index and total chlorophyll content. Mahalanobis D^2 analysis revealed that the genotypes were divided into five clusters where dry yield per plant contributed a maximum of 28.05% to the formation of clusters. The genotypes TNAUH00400028, IC255943 and TNAUH00400112 were highly divergent due to the highest inter-cluster distance associated with the genotypes. The multivariate approach provided a clear understanding of the diversity of the different genotypes where the superior lines could be utilised as the parents for the further crop improvement program.

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Authors' contributions

GS carried out the experimental work and performed the statistical analysis. KRV drafted the manuscript. VJ and KPD performed the laboratory experiments. ASA performed critical revision of manuscript. PMS and KPM carried out the laboratory experiments and drafted the manuscript. PSP performed the statistical analysis. JS gave final approval for the version to be published.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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