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SHORT RESEARCH ARTICLE

Unveilling heat-resilient chickpea (*Cicer arietinum* L.) lines under two mega chickpea growing regions in India using GGE biplot analysis

Uday Chand Jha*, Dibendu Datta[1], Shailesh Tripathi, Shayla Bindra[2], Yogesh Kumar, Surender Ghritlahre[1], Sandip Shil[3], Pardip Kumar Katiyar and Girish Prasad Dixit

Abstract

In the face of escalating uncertainties due to global climate change-induced heat stress, ensuring the stability of chickpea yields is crucial for global food security. To select stable and heat stress-tolerant genotypes, 25 advanced chickpea breeding lines, including three checks, were evaluated for various phenological, yield, and yield-related traits under diverse ecological field conditions. Under normal sown conditions, IPC2021-71 (G13), ICC92944 (G21), and IPC2019-170 (G14) showed greater stability and desirability for yield. Among these, IPC2021-71 outperformed in Kanpur, Punjab, and Bhopal based on the "which won where" criterion. Punjab and Bhopal emerged as the most informative locations based on the GGE biplot "discrimination-and-representativeness" analysis. Under heat stress conditions, stability analysis revealed that IPC2021-165 (G6), IPC2015-52 (G9), IPC2011-61 (G10), and ICC92944 (G21) were stable performers. Additionally, the "which won where" criterion highlighted G6 as the best performer in Punjab and New Delhi under heat stress conditions. Punjab and Delhi were identified as the most representative locations for heat stress.

Keywords: Chickpea, heat stress, GGE biplot, climate resilience.

Introduction

Chickpea (*Cicer arietinum* L.) plays a vital role in global food security by providing a protein-rich diet to the worldwide increasing human population (Jukanti et al. 2012). However, chickpea productivity faces significant challenges from various abiotic stresses (Jha et al. 2014). Among these, elevated environmental temperature poses a crucial obstacle to crop yields, including chickpea (Devi et al. 2022). Intense heat stress events, particularly during reproductive stages such as pod filling, significantly limit chickpea yields on a global scale (Devasirvatham et al. 2013; Devi et al. 2022). It is suggested that even a 1°C increase in seasonal temperature during the chickpea growing season could result in a yield drop of 53 kg/ha (Kalra et al. 2008).

Since yield and yield-related traits are quantitatively controlled and highly influenced by various environments and locations, understanding the genotype × environment (G × E) interactions is essential for the selection of superior genotypes. Analyses such as additive main effect and multiplicative interaction (AMMI) and GGE biplot have proven useful for gaining insights into G × E interactions and selection of stable-superior genotypes in various crops under heat stress conditions (Wu et al. 2021; Gupta et al. 2023; Li et al. 2023). However, limited research has been conducted on G × E interactions for yield trait under heat stress in chickpeas (Danakumara et al. 2023). Therefore, it is imperative to harness chickpea genetic variability

ICAR-Indian institute of Pulses Research (IIPR), Kanpur 208 024, Uttar Pradesh, India

[1]ICAR-Indian institute of Pulses Research (IIPR), Phanda 208 024, Bhopal Regional Station, India

[2]Punjab Agricultural University, Ludhiana 141 004 , India

[3]Central Plantation Crops Research Institute, Research Center, Mohitnagar, Jalpaiguri 735 102, West Bengal, India

***Corresponding Author:** Uday Chand Jha, ICAR-Indian Institute of Pulses Research (IIPR), Kanpur 208 024, Uttar Pradesh, India, E-mail: uday_gene@yahoo.co.in

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and deepen the understanding of G × E interactions in quantitatively governed traits, particularly yield to select stable and high-yielding chickpea genotypes capable of sustaining yields under rising high-temperature stress.

In this study, it was aimed to quantify genotype × environment interactions (GEI) for phenological and yield-related traits in response to heat stress among chickpea genotypes. A set of 25 advanced chickpea breeding lines were evaluated, including three checks, across four diverse locations: Kanpur, New Delhi, Punjab and Bhopal, under both normal and heat stress environments during 2022-2023 to identify genotypes with consistently high and stable yields across varied locations. This would further pave the way for their potential utilization as donors to develop climate-resilient chickpea varieties.

A set of 25 advanced breeding lines along with three checks, GNG2207, KWR108, and ICCV92944, were tested at four locations in Northern and Central zones during the *rabi*, 2022-2023 (Supplementary Table S1). The material was planted in the second week of November 2022 (normal sown) and the third week of December 2022 to impose heat stress during reproductive stages. The weekly average maximum and minimum day temperature recorded during the crop growing period across the location is given (Supplementary Fig.1). The experiment was laid out in a randomized block design with three replications. Each genotype was planted in two rows, each three meters long, with a spacing of 30 × 10 cm^2. All genotypes were assessed for yield (kg/ha). The AMMI (Agricolae) and GGE Biplot GUI packages in R software, within the R Studio environment, were used to generate AMMI and GGE biplots, respectively (R Studio, 2020). As proposed by Yan and Tinker (2006), the analysis of multilocation trial data was performed without scaling (using the 'Scaling 0' option) to obtain a tester-centered (centering 2) GGE biplot. For genotype assessment, genotype-focused singular value partitioning (SVP = 1) was employed using the GGE biplot software's 'Mean versus stability' option. For environmental evaluation, environment-focused singular value partitioning (SVP = 2) was utilized with the 'Relation among testers' option (Yan 2001). The 'Which won-where' function was employed to determine the winning/outperforming genotype across different locations.

Significant genetic variability was observed for DFF, DPOD, DM, pods/plant, seed yield/plant, and plot yield under both normal and heat stress (Supplementary Table S2) conditions at all four tested locations. Similarly, significant genetic variation for various phenological traits has been recorded in chickpeas under non-stress and heat stress sown conditions (Krishnamurthy et al. 2011; Upadhyay et al. 2011; Jha et al. 2014; Gaur et al. 2015; Devi et al. 2022).

Statistical analysis

Similarly, pooled ANOVA (Supplementary Table S2) revealed the significance of genotype × environment interactions (GEI) for all the six traits studied, demonstrating that genotype (G), environment (E), and G × E interactions significantly influenced each trait under both non-stress and heat stress conditions across the four locations as has been observed earlier, (Farshadfar et al. 2013). The ranking of all 25 genotypes based on mean yield is depicted in Fig. 1. The line passing through the biplot origin from the upper left to the lower right is known as the average environment axis (AEA). The line perpendicular to the AEA, with double arrows, indicates genotype stability. Genotypes located away from the origin along this axis exhibit high G × E interaction and low stability. According to this criterion, genotypes G13, G14, G21, and G4 were stable, while genotypes G15, G17, G3, G20 and G8 had unstable performance across the environments. Ideal stable genotype(s) exhibited both high mean performance and stability across tested environments. In the current study, genotypes G13, G14, and G4 demonstrated stability in normal sown environment across four locations. Under heat stress conditions, genotypes G6, G9, G10, and G21 were stable, whereas genotypes G8, G4, G3, and G15 were unstable in their performance. The stable genotypes identified under heat stress also exhibited high mean performance and stability. Similarly, via stability analysis, stable rice lines (Wu et al. 2021) and wheat lines (Gupta et al. 2023) have been identified under heat-stress environments.

GGE biplot analysis allows for the ranking of genotypes based on their mean performance and stability. The average environment coordination has been illustrated (Supplementary Fig. 2) by comparing genotypes relative to the ideal genotype. The arrow shows the position of the ideal genotype, with genotypes closer to this ideal being more desirable. Consequently, genotypes G13, G15, and G7 were identified as more stable and desirable. Under heat stress conditions, genotypes G8, G4, G3, and G10 exhibited greater stability and desirability. In a similar study, Srivastava et al. (2022) used GGE biplot analysis to identify stable chickpea lines *viz*., IPC17-369, IPC17-78, and IPC17-53, while Li et al. (2023) identified stable maize genotypes under rainfed

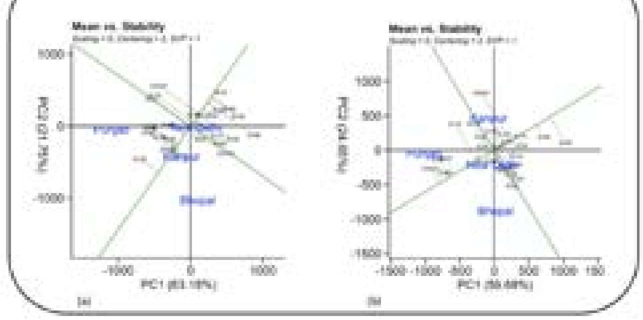

Fig. 1. Mean vs stability: Statistical analysis of genotypes (a) under no-stress condition and (b) under heat stress condition

conditions.

A "which-won-where" polygon illustrates the relationship between genotypes and environments. Genotypes positioned at the vertices of the polygon indicate the best or poor performance in specific environments. The genotypes G13, G22, G15, 8, and G11, located at the vertices, were the top performers in their respective environments (Supplementary Fig. 3). Genotypes G13 and G6 were best in performance at the Bhopal and Kanpur locations, as indicated by their position on the vertices corresponding to these locations. Similarly, genotype 13 performed exceptionally well in Kanpur, Punjab, and Bhopal, while for Delhi, it was genotype G15 and G8. Genotypes G20, G18, G16, G21, G3 and G16, not positioned at the vertices, exhibited poor performance in all environments. In contrast, genotypes G10, G4, and G5, located at the center of the polygon, demonstrated stability and high performance across all environments.

Under heat stress conditions, genotypes G6, G21, G14, and G3 appeared at the vertices, indicating they were the best performers in the respective environments. Genotype G9 was optimal in Bhopal and Delhi, genotype G6 in Punjab, and genotype G21 in Kanpur (Supplementary Fig. 3). Genotypes G2, G8, G22, G10, G2, and G8, not at the vertices, did not perform well across the environments. Genotypes G12, G13, and G5 remained at the center, demonstrating stability and high performance across all conditions. Similarly, GGE biplot analysis has been used to identify heat-tolerant rice lines (Wu et al. 2021), wheat lines (Gupta et al. 2023), and cowpea lines under rainfed conditions (Gumede et al. 2022), while no such report is documented for chickpeas.

GGE biplot "discrimination-and-representativeness" assesses the ability of environments to represent and differentiate between genotypes (Frutos et al. 2014). Among the four environments studied, Punjab and Bhopal were the most discriminating and informative, while Kanpur was the least discriminating. The average environment, represented by the small circle at the end of the arrow, reflects the «average coordinates» of all four test environments. The Average Environment Axis (AEA) is the line passing through the average environment and the biplot origin. Test environments forming a smaller angle with the AEA are more representative of other test environments (Frutos et al. 2014). Therefore, Punjab and Bhopal were the most representative, whereas Kanpur was the least representative (Fig. 2). Under heat stress conditions, Punjab and Delhi were the most representative, while Kanpur was the least representative (Fig. 2).

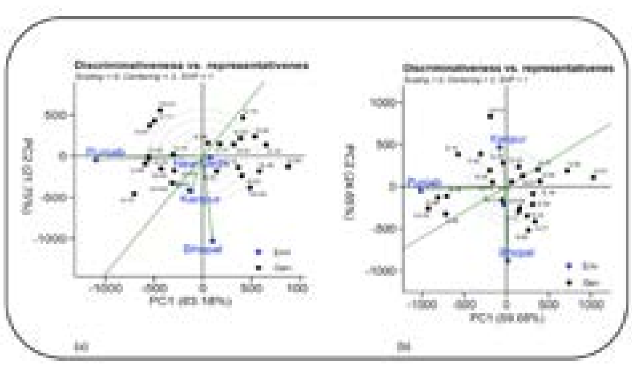

Fig. 2. Discrimitiveness vs representativeness: Statistical analysis of genotypes under (a) non-stress (b) heat stress condition

The «discrimination-and-representativeness» method has been used to select potential wheat (Bishwas et al. 2024) and rice lines (Wu et al. 2021) by testing them in various locations under heat stress. Based on the stability analysis, four genotypes, G1 (IPC2015-66), G4 (IPC2014-99), G11 (IPC2014-90), and G12 (IPC2021-168), were identified as stable performers. Additionally, the «which-won-where» criterion highlighted genotype G23 (IPC2019-02) as a top performer in Bhopal and New Delhi under heat stress conditions. These stable genotypes under heat stress conditions could potentially be used as donors for the transfer of heat tolerance traits to elite chickpea cultivars for the development of climate-smart chickpea varieties with high yield potential. Hence, IPC2015-66, IPC2015-52, IPC2014-99, IPC2014-90, IPC2021-168 and IPC2019-02 genotypes could be potentially used as donor parents for developing climate-resilient chickpea genotypes.

Supplementary material

Supplementary Tables S1 to S2 and Supplementary Figures 1 to 3 are provided, which can be accessed at www.isgpb.org

Authors' contribution

Conceptualization of research (UCJ); Designing of the experiments (UCJ, ST, DD, SB); Contribution of experimental materials (UCJ, YK, PKK); Execution of field/lab experiments and data collection (UCJ, SG); Analysis of data and interpretation (SS, UCJ, DD); Preparation of the manuscript (UCJ, GPD, PKK).

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Supplementary Table S1. List of chickpea genotypes with pedigree and their yield (kg/ha) under non stress and heat stress environment across the tested locations

Genotype code	Genotype	Pedigree	status	Kanpur (NS)	Kanpur (HS)	New Delhi (NS)	New Delhi (HS)	Punjab (NS)	Punjab (HS)	Bhopal (NS)	Bhopal (HS)
G1	IPC 2015 - 66	KWR108 × ICC1205	Advanced Breeding line	2648.1	1393.5	1908.7	1679.3	2780	1960.4	1796.5	1429.6
G2	IPC 2015 - 44	JGK1 × ICC4958	Advanced Breeding line	2634.3	2219.9	2290.7	1875	2720	1876	2202.9	1497.5
G3	IPC 2015 - 81	JG130 × ICC92944	Advanced Breeding line	2319.4	1931	2096.7	2010.7	2152.8	1069.4	2134.9	1705.6
G4	IPC 2014 - 19	ICC92944 × DCP92-3	Advanced Breeding line	2555.6	1681.5	2295	1706	2656	1736.1	2397.8	1663
G5	IPC 2014 - 55	JG315 × ICC1205	Advanced Breeding line	2713	2233.8	2490.3	1772.3	2847.2	2284.3	2362.9	1758.5
G6	IPC 2021 - 165	GNG1581 × ICC4958	Advanced Breeding line	2680.6	2025.5	2044	2042.3	2676	1879	2280.4	1925
G7	IPC 2014 - 99	KWR108 × ICC4958	Advanced Breeding line	2509.3	2106.5	2357.7	1828.3	2430.6	2035.3	2474.7	1849.7
G8	IPC 2015 - 33	ICC16614 × JG 03-16-14	Advanced Breeding line	2537	1856.5	2163.3	1878.3	1666.7	1388.9	2440.1	1585.7
G9	IPC 2015 - 52	ICC96030 × ICC1205	Advanced Breeding line	2513.9	1713	2575	2056.3	2500	1657	2098.1	1987.7
G10	IPC 2011 - 61	IPC09-50 × IPC07-88	Advanced Breeding line	2509.3	1606.5	2191	1822.7	2847.2	1548	2237.1	1741.7
G11	IPC 2014 - 90	DCP92-3 × ICC92944	Advanced Breeding line	2592.6	1767.4	2128.3	1716.3	2567	2291.7	1756.8	1687.9
G12	IPC 2021 - 168	KWR108 × JG315	Advanced Breeding line	2791.7	1689.8	2264	1671.7	2152.8	2188.6	2323.5	1908.9
G13	IPC 2019 - 171	DCP92-3 × ICC4958	Advanced Breeding line	3121.3	1881.7	2127.7	1696.7	2560	2153	2491	1496.8
G14	IPC 2019 - 170	JG130 × ICC92944	Advanced Breeding line	2629.6	1584.3	2255.3	1622.3	2708.3	1658	2663.6	1210.1
G15	IPC 2015 - 55	JG16 × IPC2004-52	Advanced Breeding line	2472.2	1714.1	2145	1673.7	2083.3	1754	1803.8	1522.5
G16	KWR 108(ch)	Released variety	Released variety	2453.7	2138.7	2678	1678.7	2786	2274.3	1669	992.2
G17	GNG 2207(ch)	Released variety	Released variety	2842.6	1817.1	2665	1943.3	2069.3	1962	2567.1	2031.2
G18	IPC 2021 - 166	JAKI 9218 × IPC04-52	Advanced Breeding line	2634.3	1675.9	2266.3	1678.7	1961.7	1827.3	2445.4	1980.6
G19	IPC 2015 - 22	JG16 × ICC92944	Advanced Breeding line	2555.6	1638	2203	1795.3	2349	1996.7	2105.1	2021.5
G20	IPC 2011 - 78	IPC09-50 × IPC09-35	Advanced Breeding line	2435.2	2000	2290.3	1887	2767	1955.3	2308.5	1578
G21	ICC 92944(ch)	Released variety	Released variety	2703.7	1773.1	1965.3	1918.3	2848.6	1897	2535.3	1967.5
G22	IPC 2019 - 1	ICC 07110 × ICC 92944	Advanced Breeding line	2375	1655.1	2319.7	1588	1900.7	1825.2	2209.3	1843.5
G23	IPC 2019 - 2	KWR108 × ICC4958	Advanced Breeding line	2541.7	1465.3	2300.7	1970	1982.4	1888.3	2027.4	2146.4
G24	IPC 2019 - 5	ICC96030 × ICC4958	Advanced Breeding line	2273.1	1365.7	2215	1888	2245	1819	2230	1998.5
G25	ICC 12213	Landrace	Landrace	2657.4	1570.6	2246.3	1967.3	2140.3	1895	2486.9	2005.6

NS=non stress

HS=heat stress

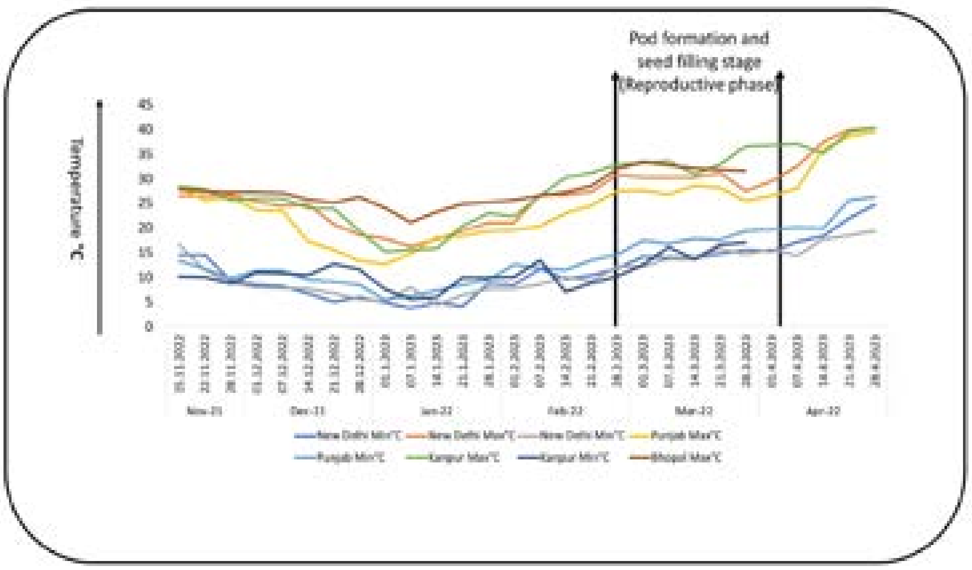
Supplementary Table S2. Combined analysis of variance for pooled data under non-stress environment

SOV	df	DF	D50F	DPI	DM	Total pods/plant	Seed yield/plant	Biomass	Yield
Genotype(G)	24	98.62**	97.759**	53.27**	25.44**	53.27**	19.21**	57.26**	9.7**
Location(L)	3	212874.7**	100284.8**	70336.7**	76269.04**	9755.1**	3673.1**	12361.8**	8236.1**
G × L	72	54.354**	41.103**	26.765**	16.193**	26.765**	16.857**	91.33**	9.4**
Pooled Error	192	1	1	1	1	1	0.999	1.001	1

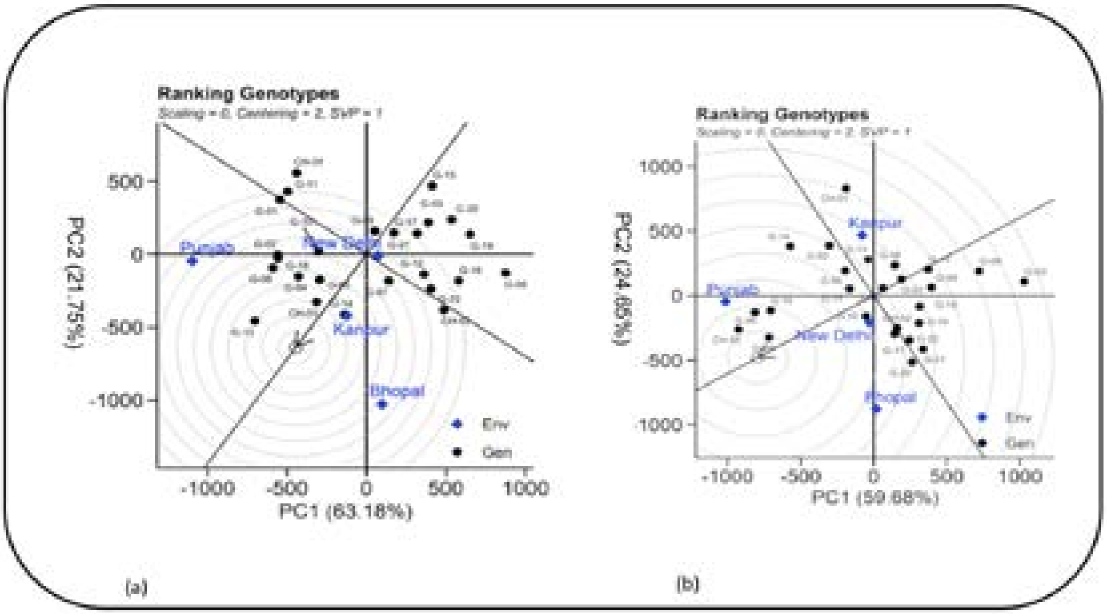
Combined analysis of variance for pooled data under heat stress environment

SOV	df	DF	D50F	DPI	DM	Total pods/plant	Seed yield/plant	Biomass	Yield
Genotype(G)	24	48.707**	80.516**	12.35**	27.718**	60.885**	5.305**	10.368**	6.88**
Location(L)	3	5758.255**	1578.946**	7998.9**	61919.1**	11481.4**	2259.7**	12304.8**	3800.8**
G × L	72	24.256**	33.895**	8.953**	12.636**	61.055**	7.315**	8.934**	6.8**
Pooled Error	192	1	1.24	1	1	1	1	1	1

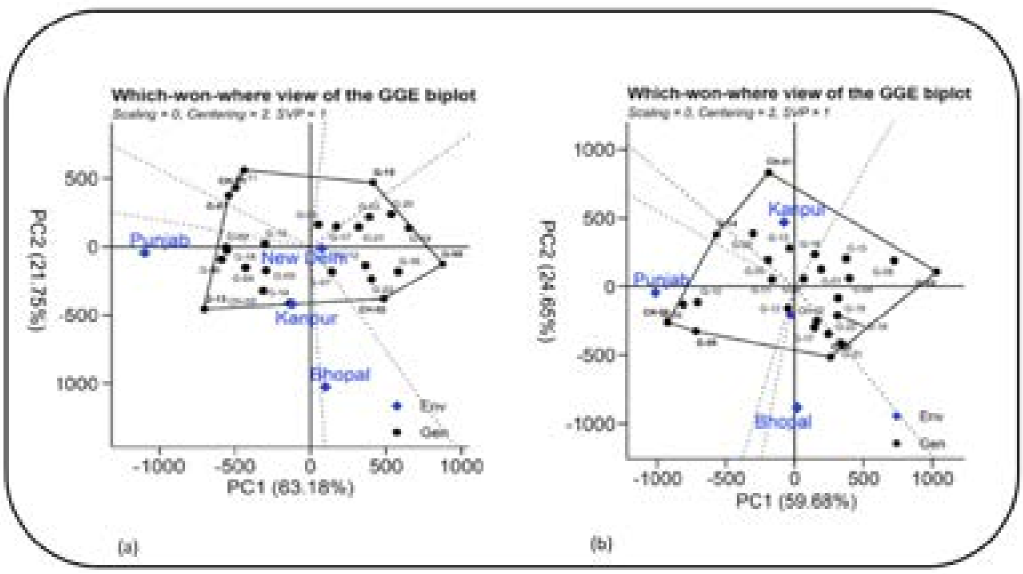
**significance at 1% level



Supplementary Fig. 1: Weekly mean day's maximum and minimum temperature recoded during the crop growing period across the various tested locations



Supplementary Fig. 2. Ranking of genotypes (a) under non-stress condition(b) under heat stress condition



Supplementary Fig. 3. "Which won where /what" analysis of genotypes(a) under non-stress and (b) under heat stress condition