GGE BIPLOT ANALYSIS OF GENOTYPE -BY-ENVIRONMENT INTERACTION FOR CAULIFLOWER YIELD

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The stability of yield and component traits in twenty-five cauliflower (*Brassica oleracea* var. *botrytis* L.*)* genotypes were studied under five sowing dates over two years at Vegetable Research Farm, Punjab Agricultural University, Ludhiana. Data were subjected to the combined analysis of variance and trait stability by GGE biplot. The significant genotype – by-environment interactions for yield along with its component traits (gross plant weight, net curd weight, leaf length, leaf width, curd height, curd width, days to curd initiation, days to curd maturation, days to bolting, bolting percentage, number of leaves plant^{-1} and stalk length) demonstrated the potential to develop the environment specific cultivars. However, the temporal fluctuations in productivity emphasized the need to select for stability over several years in potential cultivars for the target environments. Genotypes CAUEP HYB-5, CAUEP HYB-3, CAUEP HYB-9, CAUSEL-1, Kartiki-3 and LS-1 were found to be highly suitable for sowing in early season while genotype CS-16, CAUMP VAR-1 and CAUSEL-2 were suitable for sowing in mid-season in terms of curd yield. Understanding of genotype-by-environment interactions for multiple traits in cauliflower is critical for developing cultivars with high mean performance and stability in target growing environments.

Keywords: Cauliflower, environment, genotype, stability, sowing dates

INTRODUCTION

Cauliflower (*Brassica oleracea* var. *botrytis* L.) is an important cool season crop that belongs to family *Brassicaceae*. It is grown on an altitude ranging from 11-60^0 N with an optimum temperature range of 5-25^{0}C. It can withstand minimum 4^{0}C to maximum 38^{0}C temperature (RANA, 2008). Temperature ranging from 19-23^{0}C is considered best for optimum growth and development of cauliflower after curd initiation. The growth of plants from

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vegetative to curding stage is highly temperature sensitive (RAY and MISHRA, 2017). The diverse agroclimatic conditions prevailing in India varying from temperate to tropical and development of different varieties suitable for varied temperature ranges leads to year-round production of cauliflower (KARTHIKA *et al.,* 2016). Depending upon the time of availability in the market, cauliflower can be broadly classified into four maturity group's (SAVITA *et al* 2014). Planting date is an important factor determining successful cultivation of cauliflower (RAHMAN *et al.,* 2007). The Indian cauliflowers are adapted to high temperature conditions and are able to initiate curd formation at temperature higher than 20^0C (DEY *et al.,* 2019). The average temperature required for formation of curd is 17^0C whereas late cultivars form curd at 10^0C (BOSS and SOM, 1986). Curd growth is greatly influenced by variation in day and night temperature; warmer nights are beneficial for the improvement of various curd growth parameters that include curd height, weight, width etc. (RAHMAN *et al* 2013). Rise in temperature before harvesting hasten curd growth as well as increase dry matter accumulation (CEBULA *et al.,* 2005). Therefore, curd size and accumulation of dry matter content is dependent upon the prevalent temperature conditions (AJITHKUMAR, 2005). Cauliflower undergoes bolting in response to low temperature conditions for seed production. Premature bolting is a highly destructive as it deteriorates the quality of curd as well as its market value (WANG *et al.,* 2008). Cauliflower needs a temperature of 10^0C and photoperiod of 10 hours for 7-21 days for bolting which shows cauliflower is a short-day plant. Vernalization is must for bolting but not for curd formation in cauliflower (GUO *et al.,* 2004). Increase in temperature during bolting or at the end of inductive phase results in delay of flower formation as well as show morphological abnormalities in flower stalk (WIEBE, 1992).

The nature and extent of variability present in the germplasm help to measure the amount of variation present in different genotypes. Variability is genetic behavior of an individual genotype in a particular environment; therefore, evaluation of genotypes is important under differential environmental conditions (POPOVIĆ *et al*., 2024; VASILEVA *et al*., 2023; KOSEV *et al*., 2022). It augments in selecting suitable genotypes for a particular season with improved curd yield. In order to identify widely adapted and phenotypically stable genotypes under specific environment conditions, which is dependent upon extent of genotype × environment interaction for curd yield and its component traits. Genotypes are expected to perform consistently over wide range of environmental conditions (CALISKAN *et al.,* 2007). G×E interaction and stability of genotype can be used to identify and evaluate using analysis of variance and principal component analysis (GGE biplot).

MATERIALS AND METHODS

Experimental details

Twenty-five cauliflower genotypes were evaluated in this study (Table 1) under five different sowing dates over two years (Table 3) at Vegetable Research Farm, Punjab Agricultural University, Ludhiana, Punjab (30^055' N and 75^054' E longitude), India. The meteorological data on the prevailing weather conditions is presented in Table 2. The experiment was conducted using factorial Randomized Block Design (RBD) with three replications under different sowing dates (Table 3). Recommended cultivation practices were followed to raise a successful crop (ANONYMOUS, 2018). Insecticides (Decis, Indofil M-45) and fungicide (captan, thiram.) were applied at label rates to control painted bug (*Bagrada hilaris*), stem rot (*Sclerotenia scleronorum*) and other pests. The observations were recorded for fourteen quantitative

characters *viz.,* leaf height (cm), leaf width (cm), gross plant weight (g plant^{-1}), net curd weight (g^{-1}), curd height (cm), curd width (cm), curd yield (q acre^{-1}), days to curd initiation, days to curd maturation, days to bolting, bolting percentage (%), harvest index (%), number of leaves plant^{-1} and stalk length (cm).

Table 1. List of genotypes included in the study

Sr. No.	Genotypes	Code	Source
1	CAUEP VAR-2	V1	ACRIP
2	CAUEP VAR-3	V2	ACRIP
3	CAUEP VAR-5	V3	ACRIP
4	CAUEP VAR-6	V4	ACRIP
5	CAUEP VAR-7	V5	ACRIP
6	CAUEP VAR-8	V6	ACRIP
7	CAUEP HYB-3	V7	ACRIP
8	CAUEP HYB-5	V8	ACRIP
9	CAUEP HYB-6	V9	ACRIP
10	CAUEP HYB-9	V10	ACRIP
11	CAUMP VAR-1	V11	PAU, Ludhiana
12	CAUMP VAR-2	V12	PAU, Ludhiana
13	LS-1	V13	PAU, Ludhiana
14	LS-3	V14	PAU, Ludhiana
15	K-5	V15	PAU, Ludhiana
16	Kartiki-3	V16	PAU, Ludhiana
17	CS-7	V17	Private
18	CS-11	V18	Private
19	CS-12	V19	Private
20	CS-13	V20	Private
21	CS-14	V21	Private
22	CS-16	V22	Private
23	CS-17	V23	Private
24	CAUSEL-1	V24	PAU, Ludhiana
25	CAUSEL-2	V25	PAU, Ludhiana

Statistical analysis

The field data recorded and statistically analyzed using software SAS. The stability analysis and genotype × environment interaction for different genotypes was evaluated as per GGE biplot analysis using computer programme 'R 3.5.1'. The percentage of G, E and G×E sum of squares of the total variation of three sources (E+ G+ G×E) have been used to indicate the magnitude of variation contributed by each component (YAN 2001).

Table 2. The meteorological data for crop season in 2018-2019 and 2019-2020

Month	Year	TEMPERATURE (^{0}c)			Mean Relative Humidity, %	Rainfall (mm)
		Maximum	Minimum	Mean Temperature		
May	2018	39.19	24.29	31.74	34.76	19.00
June	2018	37.65	27.16	32.40	50.85	141.80
July	2018	34.26	26.65	30.46	73.60	376.60
August	2018	34.10	27.28	30.69	75.44	74.00
September	2018	32.07	24.07	28.07	75.20	250.20
October	2018	31.32	17.15	24.24	63.98	0.00
November	2018	27.00	11.80	19.40	62.77	2.60
December	2018	20.66	5.49	13.07	68.24	0.00
January	2019	18.50	6.20	12.30	71.00	66.00
February	2019	20.10	9.20	14.70	75.00	95.60
May	2019	38.00	22.10	30.00	37.00	10.40
June	2019	40.40	26.90	33.70	42.00	29.90
July	2019	34.00	26.90	30.50	72.00	218.40
August	2019	33.80	31.40	32.60	76.00	331.40
September	2019	33.20	25.50	29.40	77.00	264.80
October	2019	30.60	18.40	24.50	68.00	0.00
November	2019	25.60	13.30	19.40	68.00	35.20
December	2019	20.10	8.20	14.10	74.00	45.80
January	2020	16.56	6.71	11.63	78.42	39.80
February	2020	21.28	8.58	14.93	71.43	15.00

Table 3. Dates of sowing and transplanting

Sr. No.	Year	Dates of sowing	Dates of transplanting	Environment label
1.	2018	30th May	7th July (Early)	E1
2.	2018	25th June	28th July (Early)	E2
3.	2018	24th July	3rd September (Mid)	E3
4.	2018	25th August	5th October (Mid)	E4
5.	2018	16th September	20st October (Late)	E5
6.	2019	31st May	8th July (Early)	E6
7.	2019	26th June	29th July (Early)	E7
8.	2019	26th July	4th September (Mid)	E8
9.	2019	26th August	6th October (Mid)	E9
10.	2019	17th September	21st October (Late)	E10

Biplot analysis and its interpretation

The parameters having significant genotype or genotype × environmental interactions were analyzed with GGE Biplot (YAN, 2001) for the stability under different sowing dates. Environment centered model ($Y_{ij} - \mu - \beta_j = \alpha_i \phi_{ij}$) was used to construct GGE Biplots, where E main effect (β_j) is removed and biplot contain only G (α_I) and G×E (ϕ_{ij}) which are two sources of variations that are most relevant for G×E evaluation. The two-way genotype-by-environment data matrix was decomposed to principal components (PC) through singular value decomposition. The singular values of PC1 and PC2 were further divided into genotype and environment vectors to construct meaningful biplots. Thus, GGE Biplot graphically presents the multi-environment data in two dimensions through principal components PC1 and PC2, which are unit less measures and are depicted at x- and y-axis of biplot respectively. The percentage of total variation explained by PC1 and PC2 is presented on biplots, which indicated its validity of approximation of G and G×E of the traits investigated. GGE Biplot is a versatile software that can generate different views of biplots. The average environment coordination view is used for ranking the genotypes based on mean performance and stability (e.g. Fig 1A). This graph has two lines, the average environment axis (AEA) or average environment coordination (AEC) Abscissa and the AEC ordinate AEA is the single arrowed line, which passes through the origin of the biplot. The direction of arrowhead on the AEA points to higher mean values for measured trait; in this case; curd yield (CY). Thus, the genotype CAUMP VAR-2 (V12) had the highest and CAUEP HYB-5 (V8) had the lowest mean curd yield respectively. The second line, the AEC ordinate also called the stability line, has arrowheads at both the ends. This line also passes through the origin of the biplot and goes perpendicular to the AEA. The arrow on both the ends of the AEC ordinate points to the higher instability (or higher variability) in either direction.
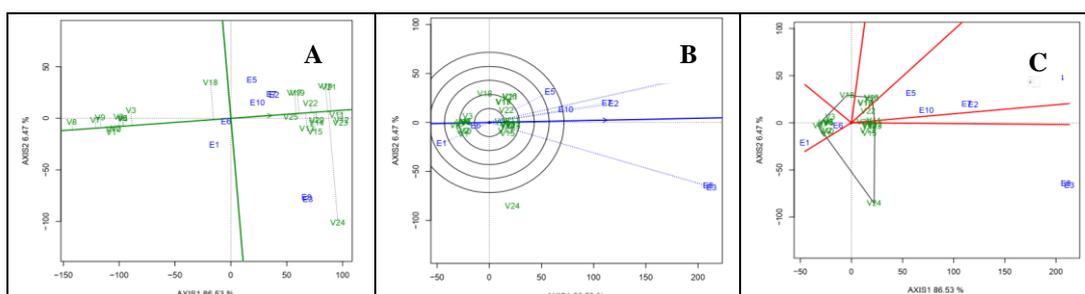

Fig.1. Average coordination view of biplot (A), discrimination, representativeness view of biplot (B) and polygon view (C) for curd yield. Genotype and environment codes are mentioned in table 1 and 3 respectively

The polygon view of the biplot presents which genotype performed the best in one or more environments (eg., Fig 1C). The best performing genotypes in specific environments are described as winning genotypes. The lines originating from the center of the biplot and the perpendicular to sides of the polygon divide the plot into different sectors. The winning genotypes for each sector are the ones located on the vertex of the polygon, *eg.,* CS-16 (V22) was specifically adapted to E2, E4, E5, E7, E9 and E10 which correspond to June, August and September sowing month in both the year.

RESULTS AND DISCUSSIONS

Analysis of variance

Table 4.1. Analysis of variance for different characters in cauliflower genotypes

Source	Character D.f.	Mean Sum Squares						
		Gross plant weight (g plant⁻¹)	Number of leaves plant⁻¹	Stalk length(cm)	Net curd weight(g plant⁻¹)	Curd height (cm)	Curd width(cm)	Leaf length(cm)
Environment (E)	9	9135445.0*	261.05*	76.14*	830490.70*	21.19*	29.39*	363.85*
Genotypes (G)	24	3561094.0*	125.97*	48.61*	330843.70*	8.35*	5.72*	153.66*
Genotype x Environment (GXE)	216	334537.20*	19.29*	6.74*	31102.92*	0.87*	1.20*	18.49*
Error	480	10004.130	0.73	0.25	282.22	0.25	0.23	2.65

Source	Character D.f.	Mean Sum Squares						
		Leaf width (cm)	Curd yield (q acre⁻¹)	Days to curd initiation	Days to curd maturation	Days to bolting	Bolting percentage (%)	Harvest index (%)
Environment (E)	9	83.12*	40938.95*	2723.44*	1213.0*	6473.0*	11525.28*	15.77
Genotypes (G)	24	36.67*	16309.02*	167.59*	73.55*	171.73*	7105.09*	10.01
Genotype x Environment (GXE)	216	6.65*	1533.22*	15.91*	7.62*	16.78*	481.39*	5.54
Error	480	0.71	13.91	1.27	4.59	1.40	115.16	9.16

* Significant at 5% level, D.f. = Degree of freedom

The analysis of variance (ANOVA) in Table 4.1 indicated that significant variation existed between different environments, genotypes and G×E interaction. The average sum of square due to environments, genotypes and G x E were significant for gross plant weight, number of leaves plant⁻¹, stalk length, net curd weight, curd height, curd width, leaf length, leaf width, days to curd initiation, days to curd maturation, days to bolting, bolting percentage and curd yield except harvest index.

Curd yield

The mean CY of all genotypes ranged from 52.15 (V8) to 118.42 (V14) q acre⁻¹. Figure 1A indicated that CAUSEL-2 (V25) was most stable for CY. In contrast, the longest vector length of CAUSEL-1 (V24) from average environmental axis (AEA) indicated this genotype having lowest stability for CY, thus contributing large G×E interactions.

Discriminative and representative views of GGE Biplot showed that E10 i.e. September was the most representative environments for CY. Moreover E3, E4, E8 and E9 which correspond to July and August sowing month in both the year showed good discriminative ability. Thus, overall test environment E2 i.e. June 2018-19 was good for selecting generally adapted genotypes for Punjab conditions (Fig 1B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for CY, genotype CS-16 (V22) was specifically adapted to E2, E4, E5, E7, E9 and E10 which correspond to June, August and September sowing month in both the year. Genotype CAUSEL-1 (V24) was specifically adapted to E3 and E8 which correspond to July sowing month in both the year. SRIVASTAVA (2001) observed significant G×E interaction for curd yield and reported maximum curd yield in August 10 sowing. ISLAM *et al.* (2016) recorded significant highest curd yield on November 15 sowing

and also reported that G×E interaction was significant for the character. RAHMAN *et al.*(2016) reported highest marketable yield per hectare (28.11t ha^{-1}) on November 15 date of planting. DIN *et al* (2007) observed significant effect of sowing dates on the yield and reported that June 16 sowing produced maximum yield (37.83t ha^{-1}). AJITHKUMAR (2005) reported that different planting dates significantly affected curd yield in both the studied years also reported that variety Snowball produced maximum yield at October 1 and 15 sowing. LAL *et al* (2005) reported significant G×E interaction for curd yield and found that Pusa Synthetic produced highest yield in September 23 sowing (Fig 1C).

Net curd weight

Likewise, CY, the mean NCW of all genotypes ranged from 234.87 (V8) to 533.37 g plant^{-1}(V14). Biplot analysis for NCW trend in mean performance and stability rankings were like CY, with CAUMP VAR-2 (V12) ranking the highest. Figure 2A indicated that CAUSEL-2 (V25) was most stable for NCW. In contrast, the longest vector length of CAUSEL-1 (V24) from average environmental axis (AEA) indicated this genotype having lowest stability for NCW, thus contributing large G×E interactions. Discriminative and representative views of GGE Biplot showed that E2, E7 and E10 i.e. June and September sowing month were most representative environments for NCW. Moreover, E3 and E8 i.e. July sowing month in both the year showed good discriminative ability. Thus, overall test environment E2 and E7 i.e. June sowing month in both the year was good for selecting generally adapted genotypes for Punjab conditions (Fig 2B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for NCW, genotype CS-16 (V22) was specifically adapted to E2, E4, E5, E7, E9 and E10 which correspond to June, August and September sowing month in both the year. CAUSEL-1 (V24) was ideal for mid–month sowing while, CAUEP HYB-5 found suitable for early sowing. LAL *et al* (2005) reported that highest net curd weight was produced by variety Pusa Synthetic under all three studied environments
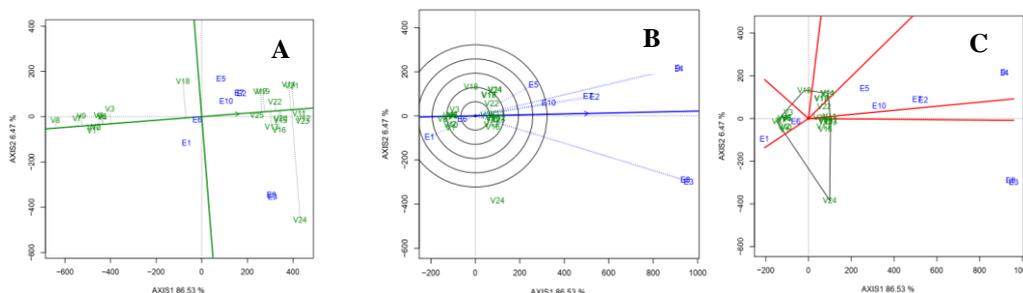

*Fig.2.Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for net curd weight. Genotype and environment codes are mentioned in table 1 and 3 respectively.*

Leaf length - LL

The mean *leaf length (*LL) of all genotypes ranged from 30.68 (V8) to 37.1 cm (V24). Figure 4A indicated that CAUSEL-1 (V25), CS-17 (V23), CAUMP VAR-2 (V12) were most stable for LL. In contrast, the longest vector length of CAUSEL-1 (V24) from average environmental axis (AEA) indicated this genotype having lowest stability for LL, thus

contributing large G×E interactions.

Discriminative and representative views of GGE Biplot showed that E2 and E7 i.e. June sowing month in both the year were the most representative environments for LL. Moreover, E3 i.e. July sowing month showed good discriminative ability. Thus overall test environment E2 and E7 i.e. June sowing month in both the year was good for selecting generally adapted genotypes for Punjab conditions (fig 4B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for LL, with that genotype CS-14 (V21) was specifically adapted to E2, E4, E5, E7, E9, and E10 which correspond to June, August and September in both the year. Genotype CAUSEL-1 (V24) was specifically adapted to E3 and E8 which correspond to July sowing month in both the year. SRIVASTAVA (2001) reported that significant variation existed for leaf length in both the years studied due to interaction. KUMARI (2017) also reported significant variation among different sowing dates and reported maximum leaf area (87.58cm^2) in sowing date of August 10. ISLAM *et al.* (2016) observed that variety Girija produced highest leaf length at November 15 and 30 date of sowing. (Fig 4C).
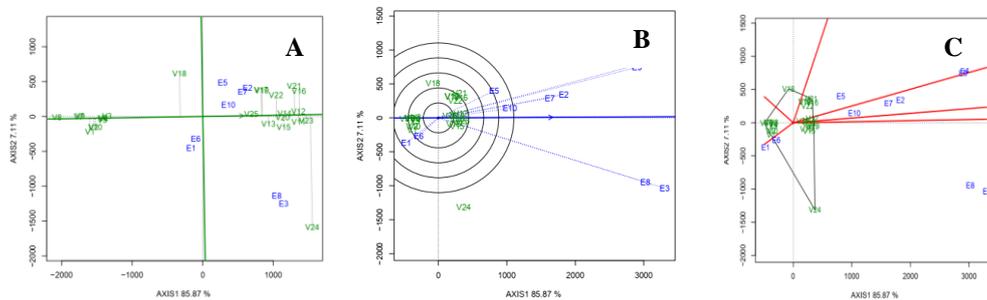

*Fig.3. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for gross plant weight. Genotype and environment codes are mentioned in table 1 and 3 respectively.*
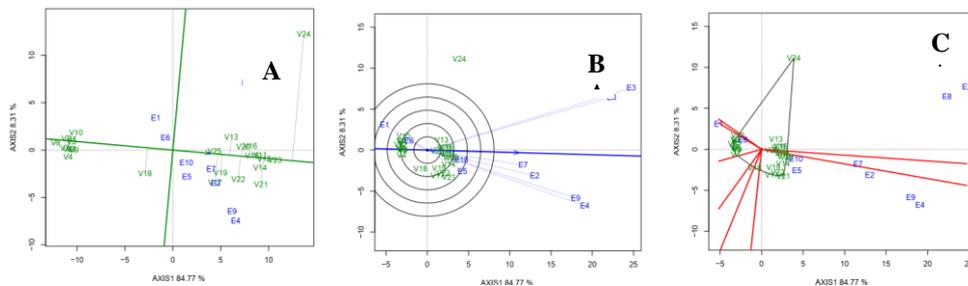

*Fig.4. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for leaf length. Genotype and environment codes are mentioned in table 1 and 3 respectively*

Leaf width -LW

The mean leaf width (LW) of all genotypes ranged from 17.49 (V8) to 21.1 cm (V24). Figure 5A indicated that CAUSEL-2 (V25) followed by CAUMP VAR-2 (V12) were most stable for LW. In contrast, the longest vector length of CAUSEL-1 (V24) from average environmental axis (AEA) indicated lowest stability for LW, thus contributing large G×E interactions. Discriminative and representative views of GGE Biplot showed that E5 and E7 i.e. September and June sowing month were the most representative environments for LW. Moreover, E3 i.e. July sowing month showed good discriminative ability. Thus overall test environment E7 i.e. June sowing month was good for selecting generally adapted genotypes for Punjab conditions (fig. 5B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for LW, with CAUSEL-1 (V24) was specifically adapted to E3 and E8 which correspond to July sowing months in both the year. Genotype CS-17 (V23) was specifically adapted to E2, E4, E7 and E9 which correspond to June and August month of sowing. CAUEP HYB-5 (V8) was specifically adapted to E1 and E6 which correspond to May sowing month in both the year. ISLAM *et al.* (2016) reported that maximum leaf width (18.56cm) was produced on November 15 by variety Girija. KUMARI (2017) observed maximum leaf width at August 10 date of sowing and reported significant variation for sowing date for leaf width. SRIVASTAVA (2001) reported that leaf width varied significantly due to G×E interaction (Fig. 5C).
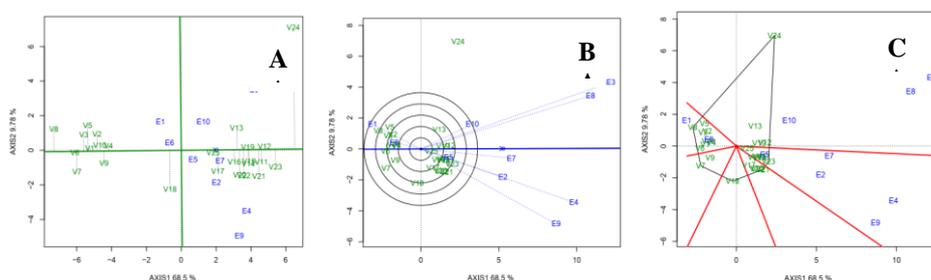

*Fig.5. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for leaf width. Genotype and environment codes are mentioned in table 1 and 3 respective*

Curd height - CH

The mean *curd height* (CH) of all genotypes ranged from 4.66 (V8) to 6.2 cm (V20). Figure 6A indicated that CAUSEL-2 (V25) followed by CAUMP VAR-2 (V12) were most stable for CH. In contrast, the longest vector length of CAUSEL-1 (V24) followed by LS-3 (V14) from average environmental axis (AEA) indicated these genotypes have lowest stability for CH, thus contributing large G×E interactions.

Discriminative and representative views of GGE Biplot showed that E10 followed by E7 i.e. September and June sowing month were the most representative environments for CH. Moreover, E3 i.e. July sowing month showed good discriminative ability. Thus, overall test environment E10 i.e. September month of sowing was good for selecting generally adapted genotypes for Punjab conditions (Fig 6B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for CH,

with LS-3 (V14) was specifically adapted to E2, E4, E5, E7 and E9 which correspond to June and August months of sowing in both the years. Genotype CAUSEL-1 (V24) was specifically adapted to E1, E3, E6 and E8 which correspond to May and July sowing months in both the year. Therefore, LS-3 (V14) was suitable for sowing in all month as it performed consistently over all environments.

Table 5. Mean performance of twenty five genotypes for thirteen traits

| Characters / Genotype	Gross plant weight (g plant^{-1})	Number of leaves plant^{-1}	Stalk length (cm)	Net curd weight (g plant^{-1})	Curd height (cm)	Curd width (cm)	Leaf length (cm)	Leaf width (cm)	Curd yield (q acre^{-1})	Days to curd initiation	Days to curd maturation	Days to bolting	Bolting percentage (%)
CAUEP VAR-2	985.63	16.19	5.98	289.65	5.07	7.05	31.45	18.18	64.31	115.23	122.23	137.35	39.67
CAUEP VAR-3	1027.05	17.24	6.12	302.42	5.04	7.34	31.67	18.48	67.14	117.48	124.48	139.80	33.33
CAUEP VAR- 5	1126.55	16.96	6.54	330.49	5.11	7.14	32.27	18.48	73.38	116.78	123.78	139.10	30.00
CAUEP VAR-6	1080.28	15.82	5.79	314.92	5.11	7.19	31.66	18.38	69.92	115.34	122.34	137.97	33.67
CAUEP VAR-7	1067.59	15.92	5.73	313.15	5.03	7.09	31.87	18.59	69.53	116.27	123.27	138.90	33.00
CAUEP VAR-8	1080.21	16.29	5.91	313.91	5.07	7.05	31.70	18.20	69.70	117.31	124.31	140.04	33.33
CAUEP HYB-3	952.09	15.45	5.25	274.50	4.92	6.99	31.32	18.21	60.95	118.71	126.71	142.34	37.67
CAUEP HYB-5	818.32	15.62	5.42	234.87	4.66	6.70	30.68	17.49	52.15	117.95	125.95	141.48	44.67
CAUEP HYB-6	943.47	16.18	5.91	276.36	4.92	6.91	31.39	18.34	61.36	117.72	125.72	140.95	35.33
CAUEP HYB-9	983.13	16.96	6.66	286.80	4.85	6.84	31.33	18.31	63.68	116.73	125.73	140.96	40.00
CAUMP VAR-1	1738.06	20.58	8.48	518.37	6.13	7.91	36.18	20.54	115.09	116.60	125.60	140.93	62.67
CAUMP VAR-2	1662.23	19.82	8.31	492.35	6.00	7.78	36.02	20.46	109.31	120.36	126.36	141.69	66.00
LS-1	1590.55	19.71	8.13	471.76	5.84	7.62	35.21	20.06	104.74	113.85	122.85	138.18	68.67
LS-3	1805.72	21.03	8.81	533.37	6.18	8.06	36.82	20.66	118.42	116.32	125.32	140.62	66.00
K-5	1670.83	19.53	7.93	502.05	5.94	7.68	36.10	19.90	111.47	117.30	124.30	139.55	67.33
Kartiki-3	1615.63	20.07	8.15	483.37	5.98	7.82	35.73	20.21	107.32	113.55	119.55	134.56	66.00
CS-7	1643.24	21.09	9.00	484.88	5.93	7.76	35.43	20.06	107.66	115.79	121.79	137.12	65.33
CS-11	1221.67	18.05	6.73	362.73	5.31	7.29	32.92	19.31	80.53	113.83	122.83	138.06	78.67
CS-12	1617.62	20.44	8.23	486.37	5.84	7.82	35.27	20.38	107.99	115.42	121.42	136.53	66.00
CS-13	1751.02	20.45	8.46	524.93	6.20	7.88	36.21	20.45	116.55	115.69	122.69	137.44	60.00
CS-14	1773.20	20.93	9.20	520.78	6.11	7.89	36.53	20.51	115.64	116.13	123.13	137.88	60.67
CS-16	1605.55	19.72	8.11	481.55	5.88	7.76	35.47	20.79	106.92	108.36	116.36	132.01	66.67
CS-17	1722.73	20.19	8.29	509.62	6.04	8.02	36.42	20.66	113.15	112.73	120.73	136.38	63.33
CAUSEL-1	1780.07	20.45	8.09	516.66	6.15	7.83	37.10	21.10	114.71	113.11	121.11	136.76	57.33
CAUSEL-2	1580.65	19.76	8.06	485.72	5.96	8.14	35.20	19.75	107.84	115.00	122.00	137.35	67.33
CD 5%	**51.26**	**0.44**	**0.25**	**8.61**	**0.25**	**0.24**	**0.83**	**0.43**	**1.91**	**0.58**	**1.10**	**0.61**	**5.50**
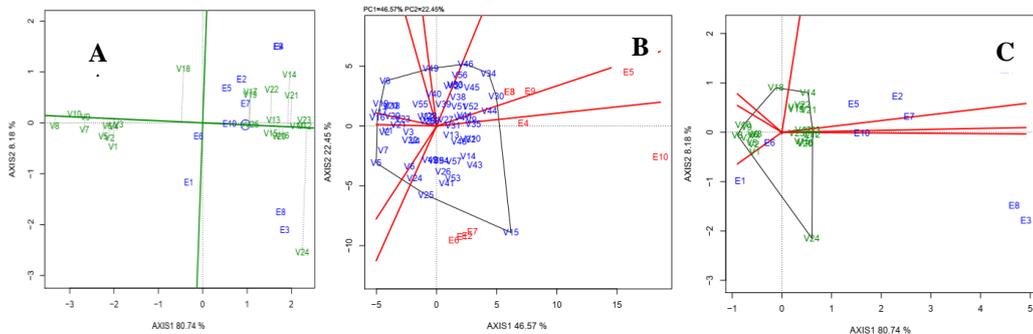
*Fig. 6. Average coordination view of biplot (**A**) Which-won-where or polygon view of biplot, (**B**) Discrimination, representativeness view of biplot (**C**) Polygon view for curd height Genotype and environment codes are mentioned in table 1 and 3 respectively*

Whereas, CAUSEL-1 (V24) was suitable for early and mid-month sowing and CAUEP HYB-5 (V8) found ideal for early sowing. SRIVASTAVA (2001) recorded maximum curd height at transplanting of July 26 for variety Pant Gobhi-4. KUMARI (2017) reported that variety Sabour Agrim observed highest curd height at August 10 date of sowing. RAHMAN *et al* (2016) stated that maximum curd height (14.53cm) was recorded at November 15 date of planting. LAL *et al* (2005) reported significant high G×E interaction for curd height and also observed maximum curd height (5.73cm) at September 23 date of transplanting (Fig. 6C).

Curd width - CW

The mean curd width (CW) of all genotypes ranged from 6.7 (V8) to 8.14 cm (V25). Figure 7A indicated CS-16 (V22) followed by Kartiki-3 (V16) and CAUMP VAR-1 (V11) were most stable for CW. In contrast, the longest vector length of CAUSEL-1 (V24) followed by CS-12 (V19) from average environmental axis (AEA) indicated these genotypes have lowest stability for CW, thus contributing large G×E interactions. Discriminative and representative views of GGE biplot showed that E9 i.e. August sowing month was the most representative environments for CW. Moreover, E3 and E9 i.e. July and August sowing month showed good discriminative ability. Thus, overall test environment E9 i.e. August sowing month was good for selecting generally adapted genotypes for Punjab conditions (Fig. 7B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for CW, CAUSEL-1 (V24) was specifically adapted to E3, E6, E8 and E10 which correspond to July, May and September sowing month. Genotype CAUMP VAR-2 (V12) was specifically adapted to E4, E5 and E7 which correspond to June, August and September month of sowing. CAUSEL-1 (V24) found ideal for mid and late month. Whereas, CS-17 (V23) and CAUEP HYB-9 (V10) found suitable for early and mid season sowing and CAUMP VAR-2 (V12) found ideal for mid-month sowing
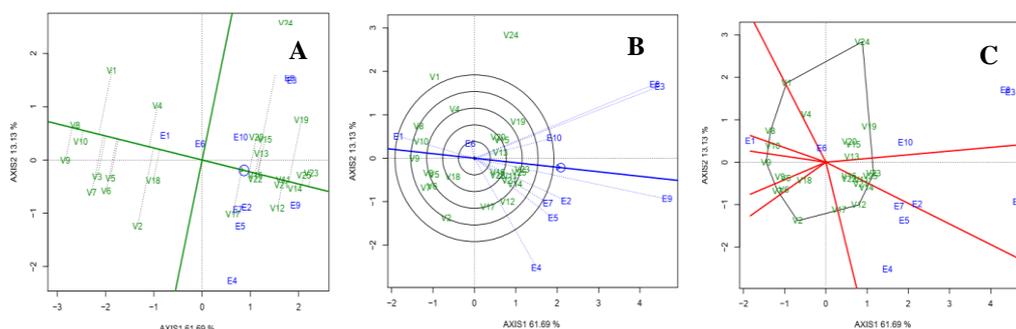

*Fig. 7. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for curd width. Genotype and environment codes are mentioned in table 1 and 3 respectively*

LAL *et al* (2005) reported significant high G×E interaction for curd diameter and variety Pusa Sharad produced maximum curd width in both September 23 and October 22 dates of transplanting. DIN *et al* (2007) reported that curd diameter enhances when early sowing is performed. RAHMAN *et al* (2016) recorded maximum curd width (22.25cm) from planting date of

November 15. ISLAM *et al* (2016) reported highest curd width in variety White Excell at planting date of November 30. KUMARI (2017) reported maximum curd width at sowing date of August 10. In contrast, SRIVASTAVA (2001) reported non-significant G×E interaction for curd width. This might be due to difference of genotypes and environmental conditions (Fig. 7C).

Days to curd initiation - DCI

The mean days to curd initiation - DCI of all genotypes ranged from 108.36 (V22) to 120.36 (V12). Figure 8A indicated CAUEP VAR-3 (V2) followed by CAUEP HYB-6 (V9) and K-5 (V15) were most stable for DCI. In contrast, the longest vector length of CS-16 (V22) followed by CAUSEL-1 (V24) from average environmental axis (AEA) indicated these genotypes have lowest stability for DCI, thus contributing large G×E interactions.
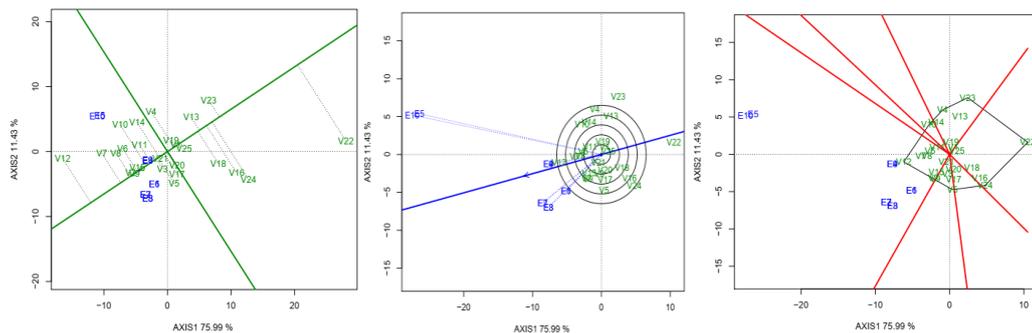

*Fig.8. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for days to curd initiation. Genotype and environment codes are mentioned in table 1 and 3*

Discriminative and representative views of GGE Biplot showed that E4and E9 i.e. August sowing month in both the year were the most representative environments for DCI. Moreover, E5 and E10 i.e. September sowing month in both the year showed good discriminative ability. Thus, overall test environment E2 and E7 i.e. June sowing month in both the year was good for selecting generally adapted genotypes for Punjab conditions (fig. 8B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for DCI, CAUMP VAR-2 (V12) was adapted to all environments which correspond to May, June, July, August and September sowing month. AJITHKUMAR (2005) reported significant difference among different planting dates for days to curd initiation and stated that Variety Snowball took least days to curd initiation in October 1 sowing. RAHMAN *et al* (2016) recorded that November 15 sowing took least number of days to curd initiation. ISLAM *et al* (2016) reported that minimum time for curd initiation (52.07) was observed in sowing of December 15 (Fig 8C).

Days to curd maturation - DCM

The mean days to curd maturation *(*DCM) of all genotypes ranged from 116.36 (V22) to 126.71 (V12). Figure 9A indicated CAUEP HYB-6 (V9) followed by CAUEP VAR-3 (V2) were most stable for DCM. In contrast, the longest vector length of CS-16 (V22) followed by Kariki-3 (V16) from average environmental axis (AEA) indicated these genotypes have lowest stability for DCM, thus contributing large G×E interactions.

Discriminative and representative views of GGE Biplot showed that E4 and E9 i.e. August sowing months in both the year were most representative environments for DCM. Moreover, E5 and E10 i.e. September sowing month in both the year showed good discriminative ability. Thus, overall test environment E2 and E7 i.e. June sowing month in both the year was good for selecting generally adapted genotypes for Punjab conditions (fig. 9B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for DCM, CAUEP HYB-6 (V9) was specifically Adapted to E2, E3, E7 and E8 which correspond to June and July sowing months in both the years. Genotype CAUEP VAR-2 (V1) was specifically adapted to E1 and E6 which correspond to May sowing month. CAUMP VAR-1 (V11) found specifically adapted to E4, E5, E9 and E10 which corresponds to August and September sowing months in both the studied years. LAL *et al* (2005) reported significant G×E interaction for days to curd maturation and found that Pusa Hybrid-2 took maximum days to curd maturation (112.66) in sowing of September 23 whereas D-928 took highest days to curd maturation (104.66 and 103.0 respectively.) in October4 and 22 sowing. ISLAM *et al.,* (2016) stated that minimum days to curd maturation were taken by December 15 sowing. RAHMAN *et al.* (2016) stated significant difference among planting dates for days to curd maturation and found that November 15 sowing took minimum days to curd maturation. Contrarily, SRIVASTAVA (2001) reported that G×E interaction was non-significant for days to curd maturation. AJITHKUMAR (2005) also reported non-significant difference for days to curd maturation among different planting dates. This might be due to difference in environmental conditions and genotypes used in their experiments (Fig 9C).
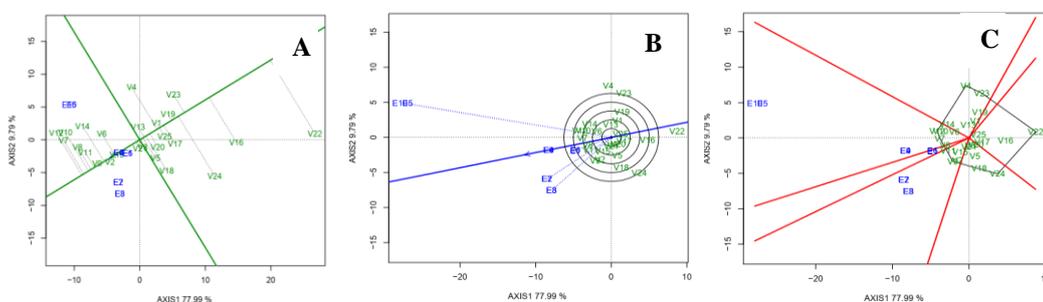

*Fig. 9. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for days to curd maturation. Genotype and environment codes are mentioned in table 1 and 3 respectivel*

Days to bolting - DB

The mean days to bolting (DB) of all genotypes ranged from 132.01 (V22) to 142.34 (V7) Figure 10A indicated CAUEP HYB-6 (V9) and CAUEP VAR-6 (V2) were most stable for DB. In contrast, the longest vector length of CS-16 (V22) was followed by genotype CAUSEL-1 (V24) followed by Kartiki-3 (V16) from average environmental axis (AEA) indicated these genotypes have lowest stability for DB, thus contributing large G×E interactions.

Discriminative and representative views of GGE Biplot showed that E4 and E9 i.e. August sowing month were the most representative environments for DB. Moreover, E5 and E10 i.e. September sowing month showed good discriminative ability. Thus, overall test environment E2 and E7 i.e. June sowing month in both the year was good for selecting generally adapted genotypes for Punjab conditions (fig. 10B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for DB, CAUEP HYB-3 (V7) was specifically adapted to E1, E2, E3, E4, E6, E7, E8, E9 which correspond to May, June, July and August in both the year. Genotype CAUMP VAR-2 (V12) was specifically adapted to E5 and E10 which correspond to September sowing month in both the year. KUMARI (2017) stated G×E interaction was significant for days to bolting and found that variety Sabour Agrim took least days (92.08) to bolting on September 10 sowing (Fig. 10C).
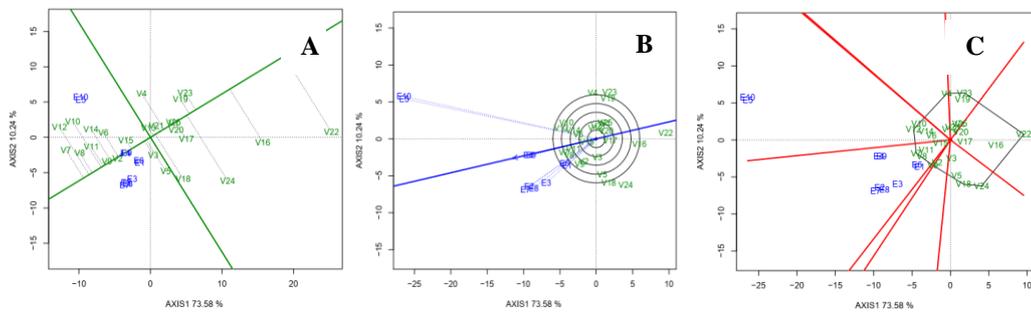

*Fig.10. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for days to bolting. Genotype and environment codes are mentioned in table 1 and*

Bolting percentage (BP, %)

The mean bolting percentage (BP) of all genotypes ranged from 30.0 (V3) to 78.67 % (V18). Figure 11A indicated that genotype CAUSEL-2 (V25) followed by CS-13 (V20) were most stable for BP. In contrast, the longest vector length of CAUSEL-1 (V24) followed by CS-16 (V22) from average environmental axis (AEA) indicated these genotypes have lowest stability for BP, thus contributing large G×E interactions.

Discriminative and representative views of GGE biplot showed that E4 and E9 i.e. August sowing month was the most representative environments for BP. Moreover, E1 i.e. May sowing month showed good discriminative ability also found good for selecting generally adapted genotypes for Punjab conditions (Fig 11B). The biplot analysis for different environments indicated a change in ranking of genotypes based on the mean performance and stability for BP in genotype CAUEHYB-3 and CAUEHYB-5 (V7 and V8) which were specifically adapted to E1, E2, E3, E4, E6, E7, E8 and E9, corresponding to May, June, July and

August sowing months of both the year. Genotype CAUSEL-1 (V24) was specifically adapted to E5 and E10 which correspond to September sowing months in both the years. KUMARI (2017) reported significant effect of environments for bolting percentage and observed that maximum bolting percentage (48.00) was observed in variety Sabour Agrim in August 10 sowing (Fig 11C).
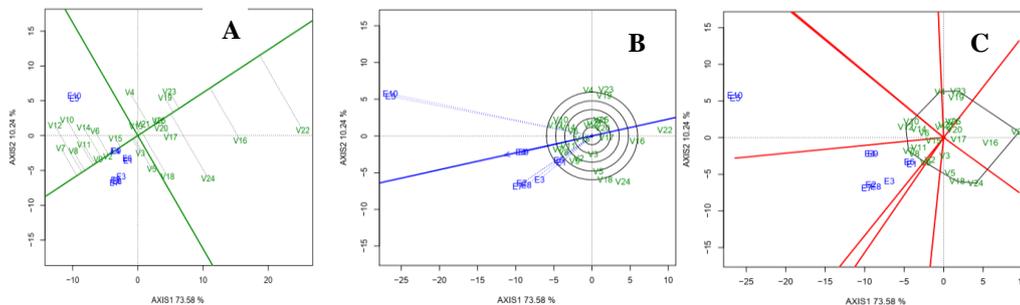

*Fig. 11. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for bolting percentage. Genotype and environment codes are mentioned in table 1 and 3 respectively.*

Number of leaves plant⁻¹(NL)

The mean *number of leaves plant⁻¹* of different genotypes ranged from 15.45 (V7) to 21.09 (V17). Figure 12A indicated CS-13 (V20) followed by CAUSEL-1 (V24) were most stable for NL. In contrast, the longest vector length of Kartiki-3 (V16) followed CAUMP VAR-2 (V12) from average environmental axis (AEA) indicated these genotypes have lowest stability for NL, thus contributing large G×E interactions.
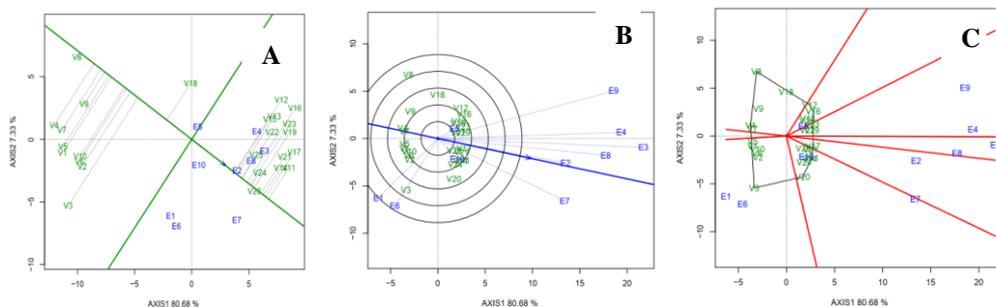

*Fig. 12. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for number of leaves. Genotype and environment codes are mentioned in Table 1 and 3 respectively.*

Discriminative and representative views of GGE biplot showed that E2 i.e. June sowing month were the most representative environments for NL. Moreover, E3 i.e. July sowing month showed good discriminative ability. Thus, overall test environment E2 i.e. June was good for

selecting generally adapted genotypes for Punjab conditions (Fig 12B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for NL, CS-17 (V23) was specifically adapted to E4 and E9 which corresponds to August sowing month in both the years. CS-7 (V17) was adapted to E2, E3, E7 and E8 that corresponds to June and July sowing month in both the year. CAUEP VAR-5 (V3) was well adapted to May month of sowing in both the years. ISLAM *et al.* (2016) observed that variety Pushpa planted on November 15 produced the highest number of leaves (19.55 per plant). RAHMAN *et al.* (2016) recorded significant G×E interaction for number of leaves (Fig. 12C).

Stalk length (SL, cm)

The mean stalk length - SL of all genotypes ranged from 5.25 (V7) to 9.2 cm (V21). Figure 13A indicated CS-14 (V21) followed by CS-13 (V20) were most stable for SL. In contrast, the longest vector length of CS-17 (V23) followed by K-5 (15) from average environmental axis (AEA) indicated these genotypes have lowest stability for SL, thus contributing large G×E interactions.

Discriminative and representative views of GGE biplot showed that E2 i.e. June sowing month was the most representative environments for SL. Moreover, E3 i.e. July sowing month showed good discriminative ability also found good for selecting generally adapted genotypes for Punjab conditions (fig. 13B). The biplot analysis for different environments indicated a change in ranking of genotypes based on mean performance and stability for SL, CS-16 (V22) was specifically adapted to E3, E4, E8 and E9 which correspond to July and August sowing month in both the years. Genotype CS-14 (V21) was specifically adapted to E2, E7, E5 and E10 which correspond to June and September month of sowing in both the years (Fig 13C).
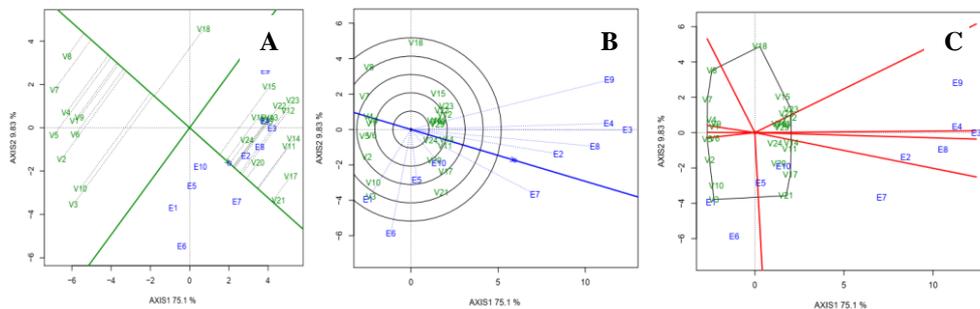

*Fig.13. Average coordination view of biplot (**A**), discrimination, representativeness view of biplot (**B**) and polygon view (**C**) for stalk length. Genotype and environment codes are mentioned in table 1 and 3 respectively*

Genotypes performance varied over different environments where environment E3 i.e. July 2018-19 was the most discriminating for the characters like curd yield, curd height, number of leaves plant[-1], stalk length, net curd weight, leaf length, gross plant weight and leaf width. Genotype LS-3 found superior for curd yield, net curd weight and gross plant weight. Whereas genotype CS-13 recorded highest curd height and maximum curd width was recorded for

genotype CAUSEL-2. The characters such as gross plant weight, net curd weight, curd height, curd width, leaf length, leaf width and curd yield recorded minimum value for genotype CAUEP HYB-5. The study on G×E revealed that genotype CS-16 found to be highly suitable for sowing in month of June, August and September, this indicates that CS-16 can be opted to grow in all the seasons that is early, mid and late. The genotype best suited for mid-season was CAUSEL-1 and for early season was CAUEP HYB-5 in terms of curd yield. The yield and yield contributing traits were most representative in E10 which corresponded to September 2019-20. Environment E2 i.e. June 2018-19 was representative as well as discriminative for the traits such as curd yield, net curd weight, leaf length, stalk length and number of leaves plant^{-1}. The characters like net curd weight (538.73g plant^{-1}), curd height, leaf length (36.87 cm), curd yield (119.61q acre^{-1}), leaf width (20.84 cm) and gross plant weight (1828.86 g plant^{-1}) recorded maximum values in environment E3 which correspond to July 2018-19. GGE biplots provide a clear view with the help of which-won-where property to find genotypes adaptable to the target environments. Hence GGE biplots can be used efficiently for the environment specific selection of genotypes.

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GGE BIPLOT ANALIZA INTERAKCIJA GENOTIP SPOLJAŠNJA SREDINA ZA PRINOS KARFIOLA

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Izvod

Stabilnost prinosa i komponenti prinosa u dvadeset pet genotipova karfiola (*Brassica oleracea* var. botritis L.) proučavana je u pet datuma setve tokom dve godine na Vegetable Research Farm, Poljoprivrednog Univerziteta u Pendžabu, Ludhiana. Podaci su podvrgnuti kombinovanoj analizi varijanse i stabilnosti osobina pomoću GGE biplota. Značajne interakcije između genotipa i spoljašnje sredine za prinos, zajedno sa osobinama komponenti prinosa (bruto težina biljke, neto težina cvasti, dužina lista, širina lista, visina cvasti, širina cvasti, dani do početka cvetanja, dani do sazrevanja cvasti, dani do zatvaranja, procenat spajanja, broj listova biljke^{-1} i dužina stabljike) pokazale su potencijal za razvoj sorti specifičnih za okruženje. Međutim, vremenske fluktuacije u produktivnosti su naglasile potrebu da se izabere stabilnost tokom nekoliko godina u potencijalnim sortama za ciljna okruženja. Genotipovi CAUEP HIB-5, CAUEP HIB-3, CAUEP HIB-9, CAUSEL-1, Kartiki-3 i LS-1 su veoma pogodni za setvu u ranoj sezoni, dok su genotipovi CS-16, CAUMP VAR-1 i CAUSEL -2 po prinosu cvasti bile pogodne za setvu u sredini sezone. Razumevanje interakcija genotip-sredine za više osobina u karfiolu je kritično za razvoj sorti sa visokim srednjim performansama i stabilnošću u ciljnim sredinama za gajenje.