



RESEARCH ARTICLE

Assessment of morpho-physiological traits for genetic diversity in field pea (*Pisum sativum* L.) under timely and late sown conditions

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Abstract

A total of 78 field pea genotypes, including four check varieties, were evaluated for morpho-physiological traits under timely and late sown conditions to assess trait associations and genetic diversity. Correlation analysis indicated that under both sowing environments, seed yield per plant (SY) was strongly and positively associated with effective pods per plant (EPP), biological yield per plant (BYP) and plant height (PH). Under late-sown conditions, 100-seed weight (HSW) also showed a significant positive relationship with seed yield (SY). These associations suggest that selection for higher EPP, biological yield (BY), PH and HSW would be advantageous for yield improvement under late sowing. Furthermore, these traits exhibited strong inter-relationships with one another across both environments. Path coefficient analysis revealed that EPP and BYP had major direct and indirect effects on SY under timely sowing, while under late sowing, EPP, BYP, HSW and PH were the key contributors. Therefore, emphasis on these traits is critical when formulating selection strategies for developing high-yielding field pea cultivars. Mahalanobis D² analysis grouped the 78 genotypes into five distinct multi-genotypic clusters under both sowing conditions. Variation in genotype distribution across environments highlighted the significant influence of environmental conditions on genotype performance.

Keywords: correlation; field pea; genetic diversity; heat stress; morpho-physiological traits; path coefficient analysis

Introduction

Field pea (*Pisum sativum* L. var. *arvense*) is an important cool-season, self-pollinated legume belonging to the family Fabaceae. Owing to its wide ecological adaptability, the crop is cultivated across diverse agro-climatic regions ranging from semi-arid tropics to temperate environments. Globally, field pea ranks second among grain legumes after common bean and is valued for its high protein content (21–25 %) and balanced amino acid profile, particularly lysine and tryptophan (1). In addition to its nutritional significance, field pea contributes to sustainable agriculture through biological nitrogen fixation, thereby improving soil fertility and reducing dependence on synthetic fertilizers (2).

In India, field pea is predominantly grown as a rabi pulse, occupying about 6.4–6.5 lakh hectares and yielding nearly 8.8–9.0 lakh tonnes annually (3). Despite steady expansion in area, productivity remains vulnerable to environmental stresses, particularly terminal heat stress under late sown conditions common in rice-pea cropping systems (4). Exposure to elevated temperatures during flowering and pod development often leads to pollen sterility, flower drop, poor pod set and reduced seed size, ultimately lowering yield (5, 6, 33).

Under changing climatic scenarios, the frequency of heat-stress events is increasing, underscoring the need to identify heat-tolerant genotypes and reliable selection traits (7–9). An understanding of genetic variability and the interrelationship among morpho-physiological traits is therefore essential for designing effective breeding strategies. Correlation and path coefficient analyses help in identifying key yield-contributing traits and their direct and indirect effects on seed yield (SY) (11–13, 15). Additionally, Mahalanobis' D² analysis provides valuable information on genetic divergence, facilitating the selection of diverse parental combinations for hybridization programs (14, 25, 30). Efficient selection for heat tolerance therefore requires a systematic and rapid approach to reliably identify genotypes with superior stress adaptation and to elucidate the key traits contributing to tolerance (8, 16). Considering these aspects, the present investigation was undertaken to evaluate field pea genotypes under timely- and late-sown conditions to assess genetic diversity, examine trait associations and identify effective selection criteria for breeding high-yielding, heat-tolerant cultivars.

Materials and Methods

Seventy-eight genotypes, including four standard check varieties, were sown under timely conditions in the first fortnight of November, while late sowing was carried out in the second fortnight of December during the Rabi season of 2024–25. The study aimed to evaluate the performance of field pea (*Pisum sativum* var. *arvense* L.) genotypes under two contrasting sowing environments that imposed terminal heat stress. The experiment was conducted using an augmented block design comprising six blocks. Each block consisted of nine test genotypes and four standard check varieties, which were replicated across all blocks to estimate experimental error. Thus, a total of 78 genotypes (including four replicated checks) were evaluated. The error variance was estimated based on the performance of the replicated check varieties across blocks. The adjusted means of test genotypes were computed using the check-variety performance method, following standard augmented design procedures. Each genotype was sown in a single row, 4 m long with a spacing of 45 cm between rows and 15 cm between plants. All recommended agronomic practices were uniformly adopted to ensure optimal crop growth. Observations were recorded on five randomly selected competitive plants per genotype for eight agro-morphological traits, namely days to 50 % flowering (DF), days to maturity (DM), plant height (PH), effective pods per plant (EPP), seeds per pod (SPP), 100-seed weight (HSW), biological yield per plant (BYP) and seed yield per plant (SYP). Days to 50 % flowering (DF) and maturity (DM) were recorded on a plot basis. In addition, two physiological traits, canopy temperature depression (CTD) and relative water content (RWC) were measured during the pod filling stage following standard protocols.

Canopy Temperature Depression (CTD)

CTD is the difference between ambient air temperature and canopy temperature, reflecting plant water status and heat tolerance. It is calculated by the following equation

$$CTD = T_{\text{air}} - T_{\text{canopy}} \quad (\text{Eqn. 1})$$

CTD was recorded during midday (12:00–14:00 hr) under clear-sky conditions using an infrared thermometer. Higher positive values indicate better water status and stress tolerance.

Relative Water Content (RWC)

RWC measures the water content of leaves relative to their fully turgid state.

The estimation of RWC was performed following the standard protocol (1) using the formula:

$$RWC (\%) = \frac{FW - DW}{TW - DW} \times 100 \quad (\text{Eqn. 2})$$

Where FW is fresh weight, TW is turgid weight and DW is dry weight.

Higher RWC values indicate better leaf hydration and drought tolerance. Turgid weight (TW) was recorded after soaking leaves in distilled water for 4 hr under ambient conditions

Statistical analysis

Mean values for each trait were computed from sampled plants and analyzed using XLSTAT software, R version 4.0 and online statistical tools developed by the Indian Agricultural Statistics Research Institute (IASRI), New Delhi. Observations were recorded for ten morpho-physiological characters of field pea, including SYP and were analyzed using appropriate statistical methods. A critical evaluation of genotype performance under timely-sown (E_1) and late-sown (E_2) conditions revealed substantial genetic variability among the field pea germplasm evaluated. Such variability provides a strong basis for identifying traits associated with yield stability and heat tolerance.

Results and Discussion

Correlation analysis

Correlation analysis was undertaken to determine the relationships between SY, its component traits and physiological parameters, which is particularly important for combining high yield potential with heat stress tolerance. Simple correlation coefficients among the studied traits were calculated separately for E_1 and E_2 environments and the results are presented in Table 1. The heatmaps (Fig. 1 and 2) depict correlations among morpho-physiological traits under timely and late sown conditions, respectively, with color gradients ranging

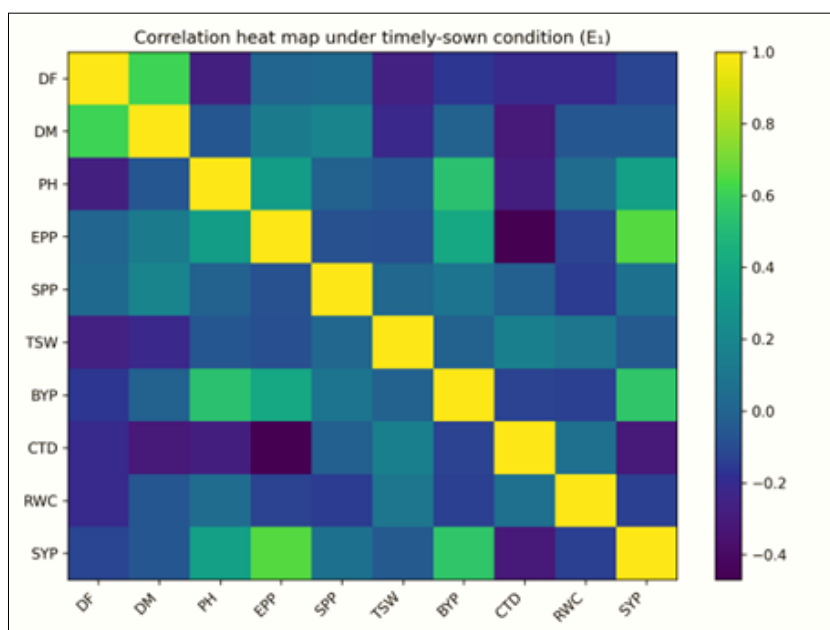


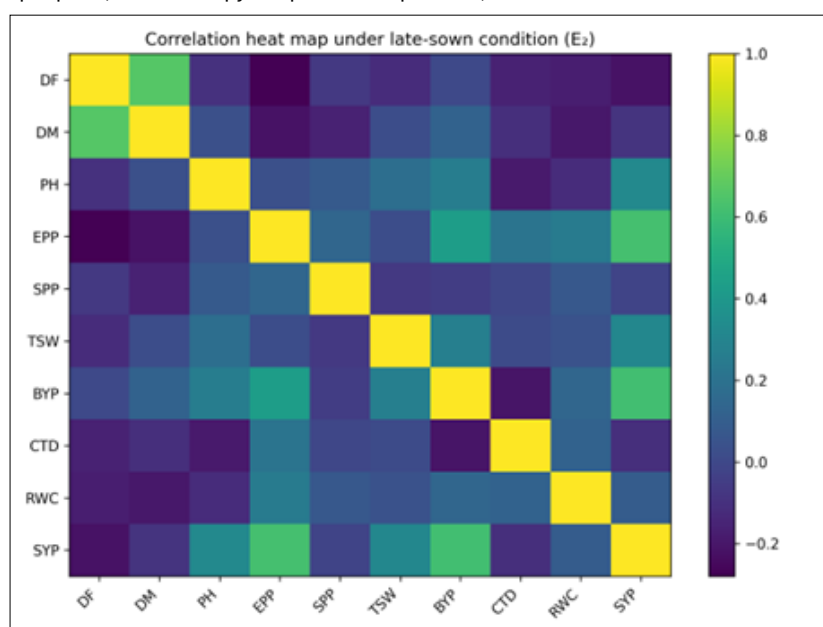
Fig. 1. Correlation heat map under timely sown condition (E_1).

Table 1. Simple correlation coefficients between different traits in field pea under timely (E_1) and late sown (E_2) conditions

Characters	Env.	DF	DM	PH	EPP	SPP	HSW	BYP	CTD	RWC	SYP
DF	E^1		0.61**	-0.27**	0.01	0.03	-0.26**	-0.16*	-0.21*	-0.21*	-0.12
	E^2		0.66**	-0.10	-0.28**	-0.07	-0.12	0.00	-0.16	-0.17*	-0.22**
DM	E^1			-0.06	0.13	0.19*	-0.22**	-0.01	-0.31**	-0.06	-0.06
	E^2			0.03	-0.22**	-0.16	0.02	0.12	-0.11	-0.20*	-0.09
PH	E^1				0.34**	-0.01	-0.06	0.54**	-0.28**	0.05	0.36**
	E^2				0.03	0.08	0.18*	0.26**	-0.19*	-0.12	0.32**
EPP	E^1					-0.08	-0.09	0.40**	-0.47**	-0.13	0.65**
	E^2					0.14	0.02	0.43**	0.21*	0.25**	0.62**
SPP	E^1						0.02	0.09	-0.02	-0.15	0.08
	E^2						-0.07	-0.05	-0.01	0.07	-0.02
TSW	E^1							0.00	0.16	0.10	-0.04
	E^2							0.27**	0.01	0.04	0.31**
BYP	E^1								-0.13	-0.14	0.56**
	E^2								-0.21*	0.14	0.61**
CTD	E^1									0.07	-0.31**
	E^2									0.12	-0.11
RWC	E^1										-0.14
	E^2										0.09

*, ** Significant at 5 % and 1 % probability level, respectively. E_1 and E_2 denote timely sown and late sown conditions.

DF = Days to 50 % flowering; DM = Days to maturity; PH = Plant height; EPP = Effective pods per plant; SPP = Seeds per pod; HSW = 100-seed weight; BYP = Biological yield per plant; CTD = Canopy temperature depression; RWC = Relative water content

**Fig. 2.** Correlation heat map under late sown condition (E_2).

from blue (negative) to yellow (strong positive) with green shades indicating moderate associations. Under timely conditions (Fig. 1), SYP showed moderate-to-strong positive correlations (green to yellow) with EPP, biological yield (BY) and PH, indicating that these traits are major contributors to yield. Under late sown conditions (Fig. 2), these associations persisted but with slightly reduced intensity, reflecting the impact of terminal heat stress. Notably, HSW exhibited relatively stronger positive association under stress conditions, while the presence of more blue and light green shades indicates weaker or negative relationships among some traits. Overall, the results suggest that trait associations are stronger and more stable under timely conditions, whereas heat stress alters the relationship among traits.

Seed yield per plant exhibited a strong and significant positive association with EPP, BYP and PH in both timely- and late-sown environments. Under late-sown conditions, HSW also showed a significant positive correlation with SY, highlighting its importance under heat stress (5, 6, 32, 33). Similar associations between yield

and its component traits have been reported previously in field pea and other grain legumes (22–25).

Under timely sown conditions, EPP showed significant positive correlations with SY, PH and BY, whereas under late-sown conditions, EPP exhibited strong associations with SY, BY, CTD and RWC. Similar associations have been reported earlier in field pea and other legumes (22–25).

Biological yield per plant showed a strong, significant positive correlation with SY, PH and EPP under timely sowing conditions (10, 24). Under late sown conditions, BYP maintained a strong association with SY indicating its importance under heat stress. Plant height was positively correlated with EPP, BYP and SYP under non-stress conditions, while under stress conditions, it showed significant associations with BYP, SYP and TSW. Additionally, under heat stress, TSW exhibited positive correlations with BYP and PH and showed a significant association with EPP. These relationships suggest that EPP, BYP, PH and TSW are desirable

selection traits for improving yield under heat stress conditions (4, 8). These findings corroborate earlier reports highlighting the importance of yield-associated traits under stress environments (4, 5, 22–24).

Path coefficient analysis was performed to partition correlation coefficients into direct and indirect effects, thereby providing insight into the causal relationships among traits influencing SY (17, 18). This approach is particularly useful in identifying key traits for effective selection. The direct and indirect effects of different traits on SYP under timely and late sown conditions are presented in Table 2. Path coefficient analysis revealed that EPP and BYP had the strongest positive direct effects on SY under timely sowing conditions. Effective pods per plant and BY also showed strong positive correlations with SY, emphasizing their importance. Traits such as BY, PH, DM and days to 50 % flowering (DF) exerted substantial indirect effects on SY through EPP, while PH, EPP and seeds per pod (SPP) contributed indirectly via BY. These results are in agreement with earlier studies in field pea (10, 11, 22, 23).

Under late-sown conditions, EPP, followed by BY, HSW and PH, emerged as major contributors to SY. These traits also maintained strong positive correlations with SY, indicating that improvement in any of these characters could enhance productivity under heat stress (5, 8, 32). The highest positive indirect effects on SY were observed through BY, RWC, CTD, SPP and PH via EPP.

Furthermore, EPP, HSW, PH, RWC and DM showed positive indirect effects on SY via BY, highlighting their contribution to yield formation under stress conditions. These observations are consistent with previous findings (8, 11).

The residual effects ($E_1 = 0.440$ and $E_2 = 0.352$) suggest that a moderate proportion of the variation in SY was explained by the traits included in the analysis, with a comparatively better model fit under late-sown conditions. Overall, the findings indicate that EPP, BY, HSW and PH are major contributors to SY under late-sown, heat-

stress conditions. Therefore, breeding strategies aimed at improving heat tolerance and yield in field pea should focus on selecting genotypes with higher pod number, increased BY, larger seed size and appropriate PH. These traits, owing to their significant direct and indirect effects on SY, should be given due consideration in breeding programs focused on developing high-yielding, heat-tolerant field pea varieties (5, 16, 32).

Genetic divergence analysis

Genetic divergence analysis using Mahalanobis' D^2 statistics revealed substantial variability among the 78 field pea genotypes, indicating the availability of diverse genetic resources for crop improvement. Analysis of divergence is essential for avoiding the repeated use of closely related genotypes and for enhancing the efficiency of crop improvement efforts. Based on D^2 analysis, the genotypes were grouped into five distinct clusters in both timely-sown (E_1) and late-sown (E_2) environments, as presented in Tables 3 and 4.

The clustering pattern varied between environments, indicating a strong influence of sowing conditions on genotype performance. Under timely sown conditions, cluster II contained the maximum number of genotypes, followed by cluster IV, whereas cluster V comprised the fewest genotypes. Under late-sown conditions, cluster II again accommodated the highest number of genotypes, followed by cluster III, while cluster IV included the fewest. This differential grouping suggests that environmental variation significantly affected phenotypic expression and mean performance of genotypes. The partitioning of germplasm into distinct clusters confirmed substantial genetic variability in the experimental material, consistent with earlier findings (1–4).

Several genotypes were grouped similarly across both environments, indicating close genetic similarity, whereas others clustered differently, reflecting greater genetic divergence. Such variation suggests the presence of both stable and environmentally sensitive genotypes within the evaluated germplasm.

Table 2. Direct and indirect effects of different traits on seed yield per plant in field pea under timely-sown (E^1) and late-sown (E^2) conditions

Characters	Env.	Direct effect	DF	DM	PH	EPP	SPP	HSW	BYP	CTD	RWC
DF	E^1	0.0053		-0.1068	0.0067	0.0054	0.0033	0.0050	-0.0560	0.0160	0.0007
	E^2	-0.0625		-0.0007	-0.0180	-0.1420	0.0061	-0.0252	0.0011	0.0236	0.0099
DM	E^1	-0.1763	0.0032		0.0016	0.0683	0.0227	0.0041	-0.0048	0.0241	0.0002
	E^2	-0.0011	-0.0412		0.0045	-0.1111	0.0141	0.0047	0.0298	0.0166	0.0119
PH	E^1	-0.0247	-0.0014	0.0112		0.1740	-0.0011	0.0011	0.1821	0.0217	-0.0002
	E^2	0.1769	0.0064	0.0000		0.0154	-0.0067	0.0376	0.0676	0.0287	0.0072
EPP	E^1	0.5159	0.0001	-0.0233	-0.0083		-0.0095	0.0017	0.1376	0.0360	0.0005
	E^2	0.5155	0.0172	0.0002	0.0053		-0.0118	0.0038	0.1092	-0.0308	-0.0151
SPP	E^1	0.1227	0.0001	-0.0327	0.0002	-0.0399		-0.0003	0.0304	0.0015	0.0005
	E^2	-0.0860	0.0044	0.0002	0.0138	0.0710		-0.0153	-0.0135	0.0022	-0.0044
TSW	E^1	-0.0189	-0.0014	0.0381	0.0015	-0.0468	0.0021		0.0000	-0.0122	-0.0004
	E^2	0.2140	0.0073	0.0000	0.0310	0.0092	0.0062		0.0697	-0.0020	-0.0022
BYP	E^1	0.3402	-0.0009	0.0025	-0.0132	0.2087	0.0110	0.0000		0.0100	0.0005
	E^2	0.2561	-0.0003	-0.0001	0.0467	0.2198	0.0045	0.0582		0.0307	-0.0086
CTD	E^1	-0.0768	-0.0011	0.0553	0.0070	-0.2418	-0.0024	-0.0030	-0.0441		-0.0003
	E^2	-0.1486	0.0099	0.0001	-0.0341	0.1067	0.0013	0.0029	-0.0529		-0.0069
RWC	E^1	-0.0035	-0.0011	0.0102	-0.0012	-0.0665	-0.0179	-0.0019	-0.0479	-0.0057	
	E^2	-0.0595	0.0104	0.0002	-0.0213	0.1306	-0.0063	0.0081	0.0370	-0.0173	

a E^1 and E^2 denote timely-sown and late-sown environments, respectively.

b DF = Days to 50 % flowering; DM = Days to maturity; PH = Plant height; EPP = Effective pods per plant; SPP = Seeds per pod; HSW = 100-seed weight; BYP = Biological yield per plant; CTD = Canopy temperature depression; RWC = Relative water content.

c Residual effect: $E^1 = 0.440$; $E^2 = 0.352$.

Table 3. Clustering pattern of 78 field pea genotypes based on morpho-physiological characters under timely-sown conditions

Cluster number	Number of genotypes	Genotypes
I	11	HUDP 15, HFP 2029, KPMR 522, LFP 431, RFP 2000-3, KPMR 928, VL 202, HFP 1802, HFP 1307, IPFD 2014-11, IPF 15-8
II	32	JP-885, KPMR 935, 02/1071, 02/1084, 02/1118, 02/1121, IC-566240, EC-552760, EC-598753, EC-341792, EC-564805, KFPG-79, KPMR 940, HF 13-14, KPMR 923, P-867, P-782, P-864, P-DMR-11, P-1434-1, P-1440-19, P-1535-2, P-781, P-201, P-1300-2-2, P-600, P-1438-1, P-729, P-1301, P-7-674-4, Adarsh, EC-595836
III	9	PFD 13-14, HFP 916, NDP 2014-4, Pant P 592, KPMR 913, EC-564817, EC-564808, EC-564803, P-1089
IV	20	IPF-21-16, KPMR 839, HF-2, IPF 16-13, P-725, P-1436-9, P-1384-1, P-1558, P-1297-11, P-1456A-3, P-647, EC-324133, EC-328743, P-122-9, P-1532, P-107, EC-324131, EC-324576, EC-564811, EC-329761
V	6	P-1450, P-1075, P-1300, P-1440-10, P-133-2-1, P-1541-16

Table 4. Clustering pattern of 78 field pea genotypes based on morpho-physiological characters under late-sown conditions

Cluster number	Number of genotypes	Genotypes
I	19	HUDP 15, HFP 2029, KPMR 522, LFP 431, RFP 2000-3, KPMR 928, VL 202, HFP 1802, HFP 1307, IPFD 2014-11, IPF 15-8, IPFD-12-02, P-1297-84, P-1297-97, P-1531, P-1613, P-1541-19, P-1589, IPFD 10-12
II	24	JP-885, KPMR 935, IC-566240, EC-552760, EC-598753, EC-341792, KPMR 940, HF 13-14, KPMR 923, P-867, P-782, P-864, P-1434-1, P-1440-19, P-1535-2, P-781, P-201, P-1300-2-2, P-600, P-1438-1, P-729, P-1301, P-7-674-4, Adarsh
III	15	P-600, P-1300, P-1384-1, Pant P 592, P-133-2-1, P-1541-16, P-1456A-3, EC-341743, P-91-3, P-1457-1, P-1658, P-647, EC-328743, P-1440-21, P-992
IV	11	P-1297-11, P-1532, P-107, EC-324131, EC-324576, EC-564811, P-864, P-729, EC-329761, P-1384-3, P-1400
V	9	P-1434-1, P-1673, P-1497, P-781, P-1300-2-2, P-179, P-1438-1, P-1450, P-263

Estimates of intra- and inter-cluster distances for the five clusters are provided in Table 5. Under timely sown conditions, cluster IV recorded the highest intra-cluster distance, followed by cluster V, indicating greater genetic variability within these clusters (14, 28, 29). In contrast, under late sown conditions, the maximum intra-cluster distance was observed in cluster V, followed by cluster I. The highest inter-cluster distance under timely conditions occurred between clusters I and V, followed by clusters I and IV, III and V and I and II. Similarly, under late sown conditions, the greatest inter-cluster divergence was observed between clusters I and V, followed by clusters I and IV, I and III and II and V. The lowest inter-cluster distance was recorded between clusters II and III under timely sown conditions and between clusters III and IV under late sown conditions, indicating close genetic resemblance among genotypes within these cluster pairs (5).

In both environments, inter-cluster distances were consistently greater than intra-cluster distances, indicating that genotypes within a cluster were relatively homogeneous. In contrast, genotypes belonging to different clusters were genetically diverse. Therefore, to generate useful recombinants in segregating generations, hybridization between genotypes from clusters with

wide inter-cluster distances-particularly clusters I and IV under timely conditions and clusters I and V under heat-stress conditions-would be most effective. Such genotypes are expected to produce high-heterotic combinations and transgressive segregants when used in hybridization, which are essential for yield improvement and breeding for stress tolerance.

Cluster mean analysis (Table 6) revealed that under timely sowing conditions, cluster I exhibited the highest mean values for HSW and CTD and lower mean values for PH, EPP, BY and SY. Cluster II recorded the lowest mean values for DM and RWC. Cluster III showed the highest mean for %DF and the lowest means for SPP and HSW. Cluster V exhibited the highest mean values for DM, PH, EPP, BY and SY, along with the lowest mean values for DF and CTD. These results indicate that cluster V exhibited higher values for SY, BY and EPP, indicating its potential as a source of high-yielding genotypes. In contrast, cluster I contributed traits like HSW and CTD.

Under late-sown (heat stress) conditions, Cluster I recorded the highest mean CTD and the lowest mean PH. Cluster II showed the lowest mean values for EPP, HSW, BY, RWC and SY. The highest mean values for DF and DM were observed in cluster III. Cluster IV exhibited higher mean values for EPP, RWC and SY, while showing

Table 5. Estimates of average intra- and inter-cluster distances among five clusters of field pea germplasm under timely (E¹) and late (E²) sown conditions

Cluster	Environment	Intra-cluster distance	II	III	IV	V
I	E ¹	26.69	71.03	44.28	102.10	130.15
	E ²	26.42	38.88	48.80	64.95	72.50
II	E ¹	28.18	—	41.41	41.85	66.69
	E ²	25.18	—	31.16	43.73	46.47
III	E ¹	28.49	—	—	67.58	96.13
	E ²	23.50	—	—	30.22	32.06
IV	E ¹	34.09	—	—	—	41.78
	E ²	22.04	—	—	—	31.18
V	E ¹	29.05	—	—	—	—
	E ²	28.01	—	—	—	—

E¹ = timely sown condition; E² = late sown condition.

Diagonal values represent intra-cluster distances, while off-diagonal values represent inter-cluster distances.

Table 6. Cluster means for morpho-physiological traits in field pea under timely (E¹) and late (E²) sown conditions

Cluster	Environment	DF	DM	PH	EPP	SPP	HSW	BYP	SYP	CTD	RWC
I	E ¹	69.50	116.80	66.81*	25.40*	4.57**	14.65**	34.21*	9.39*	16.49**	87.73
	E ²	64.72	99.75	44.76*	10.85	3.43	10.62	23.91	3.43	10.37**	74.75
II	E ¹	69.84	115.92*	132.00	30.13	4.38	12.50	44.50	14.42	14.42	86.98*
	E ²	64.07	99.55	73.84	8.96*	3.51	9.85*	18.62*	2.61*	9.77	66.42*
III	E ¹	71.75**	117.55	101.29	26.91	4.21*	12.24*	42.20	10.43	14.84	87.63
	E ²	66.16**	101.76**	86.82	10.36	3.48	10.31	32.90	4.89	7.96	71.27
IV	E ¹	67.29	116.20	161.02	34.26	4.46	12.94	57.50	15.39	14.41	89.04**
	E ²	62.92*	100.26	106.73	11.99**	3.33*	10.79	37.53**	5.82**	7.68*	75.86**
V	E ¹	66.54*	117.56**	191.84**	37.18**	4.45	13.84	61.54**	16.03**	12.30*	88.25
	E ²	63.30	98.99*	113.45**	9.12	3.73**	12.06**	23.33	4.31	9.65	68.80

E¹ = timely sown condition; E² = late sown condition.

*, ** Significant at 5 % and 1 % probability levels, respectively.

DF = Days to 50 % flowering; DM = Days to maturity; PH = Plant height (cm);

EPP = Effective pods per plant; SPP = Seeds per pod;

HSW = 100-seed weight (g); BYP = Biological yield per plant (g);

SYP = Seed yield per plant (g); CTD = Canopy temperature depression (°C);

RWC = Relative water content (%).

lower values for DF, SPP and CTD. Cluster V recorded higher mean values for PH and SPP and lower mean values for DM. These findings indicate that cluster IV performed better in SY, EPP and RWC, underscoring its importance as a source of heat-tolerant, high-yielding genotypes. While cluster I may contribute to physiological traits associated with stress adaptation. Therefore, hybridization between genotypes from divergent clusters, such as I × V (timely) and I × IV or I × V (late), are required to develop improved, heat-tolerant varieties. Such crosses are expected to produce high-heterotic combinations and transgressive segregants, which are essential for yield improvement and breeding for stress tolerance.

Overall, the results demonstrated that different clusters were superior for specific traits under different environments. Correlation and path coefficient analyses indicated that SY under both timely and late sown conditions was strongly and positively associated with EPP, BY and PH. In contrast, HSW played a critical role under heat stress. Differences in cluster mean values for yield and physiological traits across both environments further confirmed environment-specific trait expression and selection potential (20, 21, 26, 34). Consequently, hybridization among genotypes from clusters with high mean values for key yield traits and wide inter-cluster distances is likely to be effective for developing high-yielding and heat-tolerant field pea genotypes.

Conclusion

The present investigation revealed considerable genetic variability among field pea genotypes under both timely and late sown conditions. Correlation, path coefficient and divergence analyses consistently identified EPP, BY, PH and HSW as key determinants of SY, particularly under heat stress. The differential clustering of genotypes across environments further highlighted the strong influence of sowing conditions on trait expression. Therefore, strategic selection and hybridization among genetically diverse genotypes possessing favorable yield and stress-adaptive traits can accelerate the development of high-yielding, heat-tolerant field pea cultivars.

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Authors' contributions

MK and KS participated in the study design and performed the statistical analysis. AKP contributed to the analysis of physiological parameters. SPS participated in the data compilation. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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