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Genetic variability, heritability, and multivariate analysis of drought tolerance-related traits in field pea (*Pisum sativum* L.) under varying drought stresses

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Abstract

Field peas (*Pisum sativum* L.) withstand short-term drought stress. However, prolonged drought spells cause a significant reduction in grain yield up to 25%. Drought tolerance is a combination of morphological, physiological, molecular, and cellular mechanisms. Therefore, the current study aimed to quantify genetic variability and identify key physiological traits that govern drought tolerance in field peas under contrasting water stresses. Thirty-six pea genotypes were utilized to determine the inheritance of drought tolerance using a completely randomized design (CRD). Plant height, leaf area, days to 50% percent flowering, root length, shoot to root ratio, chlorophyll content, electrolyte leakage, relative water content, and proline accumulation were the key traits that were determined during this study. Highly significant differences ($P \leq 0.01$) for all traits indicated the presence of substantial genetic variability. Traits like Plant height, root length, relative water content, and chlorophyll content had high GCV, heritability, and genetic advance. This indicated strong additive gene action and suitability for selection for these. Relative water content, leaf area, and chlorophyll content were the key contributors to genetic variability under drought stress. This was confirmed by principal component analysis (PCA). Moreover, a strong positive correlation among root length, leaf area, and relative water content was observed. This highlighted their collective role in drought tolerance. On the other hand, yield per plant showed weak and inconsistent correlations under stress conditions. This indicated its complex inheritance and dependence on multiple interacting traits. This also suggested that indirect selection through key physiological traits may be more effective under drought conditions. Moreover, root length, relative water content (RWC), and chlorophyll content can be effectively used for selecting drought-tolerant genotypes.

Keywords: Peas, Drought Stress, Drought Tolerance, Abiotic Stress

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Introduction

Field pea (*Pisum sativum* L.) is a diploid ($2n=14$) belonging to the Fabaceae family. It is a self-pollinated crop (1). It is the 3rd most cultivated legume crop, following soybeans and common beans (2). According to FAO Statistics, green peas were produced at 33.76 million tons, and dry peas at 15.65 million tons. Area under cultivation was 8.29 million hectares for green peas and 4.17 million hectares for dry peas. Pakistan produced 0.397 million tons of green peas and 0.022 million tons of dry peas. Total area under cultivation of Pakistan for 0.0318 million hectares for green peas and 0.0543 million hectares for dry peas in 2024 (3).

Field peas grow best in cool-season climates with moderate temperatures ranging from 13°C to 18°C. The optimum temperature for germination is approximately 22°C, with low rainfall and low humidity. The preferred soil pH ranges from 6.0 to 7.5. Ideal soil for peas is deep loam with good drainage and moisture retention capacity. However, sandy loam is best suited for green peas, and clay loam is suitable for dry pea cultivation (4). Peas contain starch (36.9–49.0%), protein (21.2–32.9%), dietary fiber (14–26%), lipids (1.2–2.4%), and ash (2.3–3.4%) (5,6).

The nutritional composition of peas makes them valuable for human food, animal feed, and bioenergy production. Peas are

also rich in phytochemicals, galactose oligosaccharides, saponins, and polyphenolics. These compounds make peas anticarcinogenic, hypocholesterolemic, prebiotic, and a good source of antioxidants (5).

The pea crop is highly affected by various biotic and abiotic stresses. However, abiotic stresses are becoming increasingly significant due to climate change (7). Cold, waterlogging, and drought stress are the key abiotic stresses. Drought is considered the most prevalent and damaging among the abiotic stresses. It results in up to 50% of crop yield losses worldwide, especially in arid and semi-arid regions. However, yield losses depend upon the severity and duration of drought spells. Moreover, it depends on cultivar, soil characteristics, agro-climatic conditions, and developmental stages of plants (8). Under field conditions, yield losses of up to 25% have been reported due to drought stress. Studies showed that Peas can withstand short-term drought stress (9). Moreover, Projections indicate that global drought frequency could increase by up to 20% by the end of the 21st century due to climate change (10). If this happens, it may cause more serious damage to the peas, especially the yield. For this, there is a need for breeding for drought stress in peas.

To combat drought, plants employ three strategies: drought tolerance, drought escape, and delayed dehydration. Drought tolerance is broadly defined as a plant's capacity to withstand drought through mechanisms such as dehydration avoidance and drought escape (11). However, drought tolerance is a complex trait encompassing morphological, physiological, biochemical, molecular, and cellular mechanisms (12). These strategies form the basis for breeding drought-resilient cultivars. While some drought tolerance mechanisms are common across plant species, others are species-specific, making the overall understanding of drought tolerance complex (13). Despite this complexity, the development of drought-tolerant cultivars remains a key objective in plant breeding programs (11). Several studies have investigated drought responses in legumes. However, studies on genetic variability and interactions among traits under contrasting moisture regimes in field pea remain limited. Furthermore, the identification of reliable selection criteria for drought tolerance is essential for accelerating breeding programs. Therefore, the present study was designed to identify key drought-associated traits. It will provide practical information for indirect selection and the development of drought-resilient pea cultivars. We evaluated 36 genotypes of pea under three drought stress conditions. We studied the varying performance of morphological, physiological, and biochemical traits associated with drought adaptation. Morphological traits included plant height, leaf area, days to 50% flowering, root length, shoot to root ratio, and yield per plant. Physiological traits included electrolyte leakage and relative water content, while biochemical traits included chlorophyll content and proline accumulation. Studying these traits is crucial for deciphering the complex mechanisms underlying drought tolerance.

Materials and Methods

Plant material

Plant material consisted of thirty-six pea genotypes. Genotypes were obtained from the Barani Agricultural Research Institute (BARI), Chakwal. These materials were selected to maximize genetic diversity. Fuhrer, to emphasize their differing adaptation and their potential response to drought-stress conditions. The list of these genotypes is given in Table 1.

Table 1: Pea genotypes under study for evaluation of drought tolerance

Sr #.	Name	Sr #	Name
1	Climax	19	DP-17020
2	Meteor	20	BCI-19737
3	FSD-01	21	BCI-18293
4	21B010	22	BCI-18318
5	RMR-1907	23	BCI-18342
6	20B008	24	BCI-18370
7	Supreme	25	BCI-18371
8	Snow Peas	26	MID-No. 13
9	Ambassador	27	BCI-18375
10	F. Field Selection	28	MID-No. 15
11	DP-17001	29	FW-1
12	DP-17002	30	MID-No.11
13	DP-17018	31	BCI-18275
14	DP-17019	32	FW-4
15	Barani Matar	33	FW-2
16	BCI-26871	34	PIL-No. 6
17	Sarsabz	35	FW-3
18	BCI-19744	36	BCI-26875

Study design and growth conditions

The experiment was conducted in control environment in Pir Mehr Ali Shah Arid Agriculture University (latitude 33.6°N, longitude 73.04°E) in 2023. The recorded temperature during the experiment is given in Figure 1. The inside temperature was 15.5°C to 21.5°C during the day and 11.5°C to 16°C at night. While relative humidity inside the greenhouse ranged from 55 to 70%. Plants were exposed to natural photoperiod conditions. The study was carried out under the Completely Randomized Design (CRD) with three replications. Plants were grown in plastic disposable cups (95 mm diameter and 106 mm height). 300 g of a homogeneous potting mixture consisting of sand, soil, and farmyard manure (1:1:1) was filled in each cup. We made a small drainage hole at the bottom of each cup to facilitate the removal of excess water. To prevent seed-borne diseases, fungicide (Thiram) was used to treat the seed of each genotype. After germination, seedlings were thinned to maintain three plants per cup. Drought stress was initiated after 21 days of germination. It lasts up to the plant's maturity. Three levels of field capacity (FC) were maintained: T₁ (100% FC, control), T₂ (60% FC, moderate drought stress), and T₃ (40% FC, severe drought stress). Based on field capacity determination, 100% FC corresponded to 122 mL of water per 300 g of soil. Accordingly, 60% FC and 40% FC were maintained by applying 74 mL and 49 mL of water per pot, respectively. Field capacity was determined using three randomly selected samples. Pots were saturated with water

and allowed to drain for 72 hours, after which the weight of moist soil was recorded. The soil was then oven-dried to obtain dry weight. Field capacity was calculated on the basis of difference between moist and dry soil weights, following standard procedures and formula (14). Table 2 shows that stress levels were imposed (14). We applied the amount of water required for each field-capacity level at regular intervals throughout the experiment.

$$\text{SWC (\%)} = \frac{\text{Mass of moist soil (g)} - \text{Mass of oven dried soil (g)}}{\text{Mass of oven dried soil (g)}} \times 100$$

Table 2: Water stress level of controlled and experimental units in pea genotypes

Treatment	Field Capacity	Drought Stress Level	Quantity of water (ml)
T ₁	100 %	Control	122
T ₂	60%	Moderate stress	74
T ₃	40%	Severe stress	49

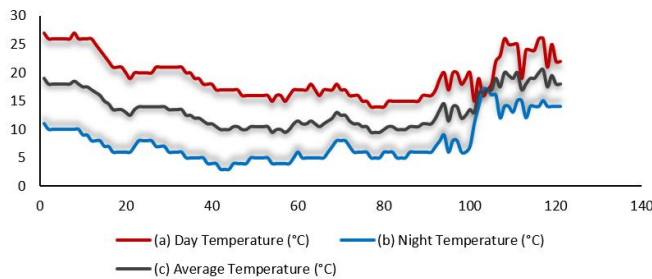


Figure 1: External temperature during (a) daytime (b) nighttime (c) average temperature

Data collection

After the stress was imposed, the data were collected from each genotype as the mean value of three plants for each parameter. Drought tolerance-related data for various morphological and physiological traits were measured. Traits like plant height, root length, shoot-to-root ratio, and days to 50% flowering were measured manually. Leaf area was measured manually, using a ruler and the following formula; Leaf Area=leaf length × leaf width × Correction Factor with a pea's correction factor of 0.72.

Electrolyte leakage was determined using 1 cm discs from fully expanded leaves. Leaf discs were rinsed with distilled water and immersed in 10 mL of deionized water. Initial electrical conductivity (EC1) was measured using a HANNA 215 EC meter after incubation at room temperature for 24 h. Samples were then autoclaved at 121°C for 20 min. Then cooled to room temperature before measuring the final conductivity (EC2). Electrolyte leakage % was calculated as: EL (%) = (EC1/EC2) × 100.

The relative water content (RWC) was measured from control and water-stressed plants according to Barrs & Weatherley (1962). Fully mature fresh leaves were weighed

(0.5g) from each genotype to get fresh weight (FW). Then, leaves were hydrated overnight in distilled water to determine the turgid weight (TW). Samples were oven-dried at 60 °C for 48 h and weighed to obtain the dry weight (DW). The percentage of relative water Content was determined using the following formula. $\text{RWC \%} = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \times 100$.

Leaf chlorophyll content was measured using the SPAD 502 chlorophyll meter. For each replication, three plants were selected for measurement. Higher SPAD values correspond to greater chlorophyll content. However, lower values indicate reduced levels.

To measure proline content, we weighed 0.5 g of fresh leaves. The pea tissues were first extracted using 10 mL of 3% aqueous sulphosalicylic acid in a pre-chilled mortar and pestle. Then, centrifuged at 10,000 × g for 15 minutes. This resulted in protein precipitation, leaving free proline in solution. The supernatant was collected in a clean tube, and 2 mL of the supernatant was pipetted out into a new test tube. Then, added 2 mL of glacial acetic acid and 2 mL of the acid ninhydrin reagent. After it, incubated the mixture in a boiling water bath (100°C) for 1 hour. Transfer the tubes to an ice bath immediately to stop the reaction. Add 4 mL of toluene to the reaction mixture. Vortexed the mixture for 20–30 seconds to extract the red chromophore into the toluene layer. Allowed the mixture to clearly separate into the top and bottom layers. Carefully collect the upper toluene phase using a pipette and transfer it to a cuvette. Finally, the absorbance was measured at 520 nm using a spectrophotometer. The proline content was measured in terms of optical density (OD) (16). Seed yield per plant was determined using three plants from each replication. All pea seeds from a single plant were weighed, and the average weight was kept as the yield per plant.

Statistical analysis

The data recorded for all studied traits were subjected to statistical analysis using appropriate methods to evaluate the contribution of each trait to drought tolerance. Analysis of variance (ANOVA) was conducted in RStudio to assess the significance of differences among genotypes and treatments using the Agricolae Package in RStudio. The means were compared using the least significant difference (LSD) test at 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) levels of probability.

Correlation analysis was performed to determine the relationships among drought-related traits using the Corrplot Package in R Studio, while the package was used for Principal Component analysis. Furthermore, Principal Component Analysis (PCA) was performed using FactoMineR to identify the principal traits contributing to variation among the genotypes under both control and drought conditions.

Results

Analysis of variance

Analysis of variance (ANOVA) revealed highly significant differences ($P \leq 0.01$) among genotypes for all ten morphological and physiological traits studied under two water regimes. While there is no significant difference between the replications and small error variances across all the traits (Table 3).

Table 3: Mean squares of drought tolerance-related traits in peas under the (a) control (b) moderate stress (c) severe stress

SOV	Control			Moderate Stress			Severe Stress		
	Genotypes	Replication	Error	Genotypes	Replication	Error	Genotypes	Replication	Error
DF	35	2	70	35	2	70	35	2	70
DTF	106.77**	16.59	15.11	112.15**	1.15	2.50	107.08**	18.36	8.48
PH	897.30**	0.10	0.30	447.20**	0.00	0.10	155.44**	0.04	13.64
RL	22.437**	0.022	0.021	6.180**	0.000	0.003	12.237**	1.521	0.795
SRR	11.091**	0.033	0.246	9.606**	3.799	1.233	1.2611**	0.0576	0.1485
RWC	905.00**	0.10	1.30	901.90**	1.40	12.00	590.70**	34.20	125.90
LA	22.619**	0.176	0.447	14.704**	0.397	0.311	6.724**	0.475	0.535
CC	95.51**	0.10	0.09	26.292**	0.000	0.579	65.94**	18.79	6.51
EL	55.58**	0.86	1.35	114.62**	0.16	0.32	148.46**	0.86	10.32
PC	0.0027179**	0.0000199	0.0000689	0.0027572**	0.0001362	0.0000581	0.0011818**	0.0001215	0.0001778
YPP	16.415**	0.116	7.357	29.303**	9.060	8.741	18.020**	2.485	3.822

*Significant at $P \leq 0.05$, **Significant at $P \leq 0.01$, ns: Non-Significant $P > 0.05$, DF= degree of freedom, DTF=days to flowering, PH= plant height, RL= root length, SRR= shoot to root ratio, RWC= relative water content, LA= leaf area, CC=chlorophyll content, EL= electrolytic leakage, PC= proline content, YPP = yield per plant (g)

Genetic variability, heritability, and genetic advance

The estimates of genetic parameters for drought tolerance-related traits under different water regimes revealed considerable variability among the evaluated pea genotypes. Under control conditions, higher PCV values were observed for shoot-to-root ratio (46.76%), plant height (34.59%), chlorophyll content (34.17%), root length (31.79%), and relative water content (32.01%). Correspondingly, these traits exhibited high GCV values. In contrast, yield per plant showed comparatively lower GCV (2.80%) and PCV (5.20%) values. Under moderate drought stress conditions, the shoot-to-root ratio exhibited the highest variability with PCV (70.81%) and GCV (58.97%), followed by plant height (34.86%, 34.86%), leaf area (33.44%, 32.41%), and relative water content (32.38%, 31.74%). Under severe drought stress conditions, relatively high PCV and GCV were still observed for traits such as shoot-to-root ratio (47.03%, 39.74%), chlorophyll content (33.26%, 28.86%), leaf area (32.12%, 28.62%), plant height (31.01%, 27.32%), and electrolyte leakage (23.57%, 21.30%).

Under control conditions, very high heritability estimates were recorded for plant height (0.9989), root length (0.9971), relative water content (0.9957), and chlorophyll content (0.9971). In contrast, yield per plant showed relatively low heritability (0.2910) under control conditions (Table 4).

Under moderate drought stress conditions, heritability estimates remained high for most traits, particularly plant height (0.9997), root length (0.9985), electrolyte leakage (0.9917), and relative water content (0.9610), given in Table 5. Under severe drought stress conditions, moderate to high heritability values were including root length (0.8276), electrolyte leakage (0.8169), days to flowering (0.7950), and leaf area (0.7939). However, relative water content and yield per showed comparatively lower heritability values of 0.5518 and 0.5533 (Table 6).

Principal component analysis

Principal component analysis (PCA) was performed to determine the contribution of morphological and physiological traits to total variability among 36 field pea genotypes under control, moderate stress, and severe stress conditions presented in Table 7. The eigenvalue and variance

estimates indicated that the first two principal components (PC1 and PC2) accounted for a substantial proportion of the total variation across all environments. strong positive loadings for plant height (0.89) and shoot-to-root ratio (0.86), whereas electrolytic leakage (-0.58) contributed negatively.

Table 1: Estimates of genetic parameters for drought tolerance-related traits under control conditions

Trait	PV	GV	GCV	PCV	ECV	H ²	GA
DTF	45.66	30.55	10.09	12.33	7.09	0.67	9.31
PH	299.31	298.99	34.57	34.59	1.12	1.00	35.60
RL	7.49	7.47	31.75	31.79	1.70	1.00	5.62
SRR	3.86	3.62	45.25	46.77	11.79	0.94	3.79
RWC	302.52	301.23	31.95	32.01	2.09	1.00	35.68
LA	7.84	7.39	31.77	32.72	7.81	0.94	5.44
CC	31.90	31.81	34.13	34.18	1.85	1.00	11.60
EL	19.42	18.08	25.58	26.51	6.98	0.93	8.45
PC	0.00	0.00	27.16	28.63	7.52	0.90	0.06
YPP	10.38	3.02	2.81	5.20	4.38	0.29	1.93

Table 2: Estimates of genetic parameters for drought tolerance-related traits under moderate stress conditions

Trait	PV	GV	GCV	PCV	ECV	H ²	GA
DTF	39.05	36.55	11.35	11.73	2.97	0.94	12.05
PH	149.09	149.04	34.86	34.87	0.65	1.00	25.14
RL	2.06	2.06	7.97	7.98	0.30	1.00	2.95
SRR	4.02	2.79	58.97	70.81	39.20	0.69	2.87
RWC	308.64	296.61	31.75	32.38	6.39	0.96	34.78
LA	5.11	4.80	32.41	33.45	8.25	0.94	4.37
CC	9.15	8.57	18.23	18.84	4.74	0.94	5.84
EL	38.42	38.10	26.11	26.22	2.39	0.99	12.66
PC	0.00	0.00	14.89	15.69	3.78	0.90	0.06
YPP	15.60	6.85	6.10	9.20	6.89	0.44	3.58

Under moderate and severe stress conditions, PC1 remained largely associated with relative water content, leaf area, and chlorophyll content, indicating that maintenance of water status and photosynthetic traits is crucial under drought. However, root length showed negative loading under stress. PC2 was consistently dominated by plant height and shoot-to-root ratio, while proline content and electrolytic leakage showed negative loadings (Figure 2).

The first two principal accounts for a cumulative variance of 54.91% under control conditions, 49.41% under moderate stress, and 55.44% under severe stress of the total variability. Under control conditions, PC1 was mainly influenced by relative water content (0.95), root length (0.93), leaf area (0.93), and chlorophyll content (0.79), indicating that this component represents plant water status and photosynthetic capacity, while days to flowering (-0.18) and electrolytic leakage (-0.14) showed negative associations. PC2 showed

Pearson's correlation

Pearson's correlation analysis was performed to assess relationships among 10 morphological and physiological traits across 36 pea genotypes under control, moderate drought, and severe drought stress (Figure 3). Under control conditions, root length showed a strong positive association with leaf area (0.99), indicating that genotypes with more developed root systems tended to have larger leaf areas. Similarly, Relative water content (RWC) exhibited strong positive correlations with chlorophyll content (0.83), root length (0.82), and leaf area (0.81). Plant height also showed a positive correlation with the shoot-to-root ratio (0.82). This indicates that taller plants tended to have a higher shoot-to-root ratio under optimal moisture conditions. Electrolyte leakage (EL) showed a negative correlation with plant height (-0.38) and leaf area (-0.32). Similarly, the proline content and days to 50% flowering have a moderate negative correlation (-0.34).

Under moderate drought stress conditions, plant height showed a strong positive correlation with root length (0.73). Relative water content maintained strong positive correlations with chlorophyll content (0.73) and leaf area (0.82). Similarly, root length was negatively associated with the leaf area (-0.59) and relative water content (-0.39).

Under severe drought stress conditions, Plant height had a positive correlation with the shoot-to-root ratio (0.81). However, relative water content remained positively associated with chlorophyll content (0.76) and leaf area (0.71). Leaf area showed a negative correlation with root length (-0.69). Similarly, days to 50% flowering is negatively correlated with the chlorophyll content (-0.45).

Discussion

The highly significant genotypic differences indicated a high genetic variability among the evaluated thirty-six genotypes. Such variability is critical for selection in pea breeding for drought tolerance and yield stability. These findings are consistent with (17). The study indicated that traits such as leaf area, chlorophyll content, and plant growth show a considerable genetic variability among genotypes. High phenotypic and genotypic coefficients of variation (PCV and GCV) for traits such as shoot-to-root ratio, plant height,

chlorophyll content, root length, and relative water content indicate substantial inherent variability. In contrast, lower variability observed for yield per plant suggests a greater influence of environmental factors. The narrow differences between PCV and GCV for plant height, root length, relative water content, and chlorophyll content indicate that these traits are largely governed by genetic factors with minimal environmental influence, making them reliable for selection. Conversely, wider differences for traits such as shoot-to-root ratio and yield per plant reflect stronger environmental effects on their expression.

Table 3: Estimation of genetic parameters for drought tolerance-related traits under severe stress

Trait	PV	GV	GCV	PCV	ECV	H ²	GA
DTF	41.34	32.87	10.94	12.27	5.56	0.80	10.53
PH	60.90	47.27	27.32	31.02	14.68	0.78	12.48
RL	4.61	3.81	9.08	9.98	4.14	0.83	3.66
SRR	0.52	0.37	39.74	47.03	25.15	0.71	1.06
RWC	280.81	154.95	19.60	26.39	17.67	0.55	19.05
LA	2.60	2.06	28.62	32.12	14.58	0.79	2.64
CC	26.32	19.81	28.86	33.26	16.55	0.75	7.95
EL	56.37	46.05	21.31	23.57	10.09	0.82	12.63
PC	0.00	0.00	5.93	7.66	4.57	0.60	0.03
YPP	8.55	4.73	6.75	9.08	6.07	0.55	3.33

PV = Phenotypic Variance, GE = Genotypic Variance, GCV = Genotypic Coefficient of Variance, PCV = Phenotypic Coefficient of Variance ECV = Environmental Coefficient of Variance, H² = Broad Sense Heritability, GA = Genetic Advance

Table 4: Principal component analysis of different morphological, physiological and biochemical traits in genotypes under (a) controlled (b) moderate stress (c) severe stress conditions of the field pea crop

	Control		Moderate Stress		Severe Stress	
	PC1	PC2	PC1	PC2	PC1	PC2
Eigen values	3.35	2.15	2.84	2.11	2.94	2.60
% Variance	33.46	21.45	28.35	21.06	29.41	26.02
Cumulative %	33.46	54.91	28.35	49.41	29.41	55.44
Trait						
DTF	-0.18	-0.31	-0.30	0.08	-0.51	0.15
PH	-0.05	0.89	0.08	0.89	-0.02	0.87
RL	0.93	-0.20	-0.54	0.18	-0.57	0.28
SRR	0.06	0.86	0.46	0.70	0.07	0.85
RWC	0.95	0.03	0.95	-0.10	0.89	0.08
LA	0.93	-0.17	0.85	-0.23	0.87	-0.22
CC	0.79	0.17	0.72	0.17	0.84	0.11
EL	-0.14	-0.58	-0.12	-0.57	-0.22	-0.61
PC	0.14	0.27	0.18	-0.49	-0.21	-0.65
YPP	0.15	-0.03	-0.22	0.38	0.12	-0.41

PH= plant height, RL= root length, SRR= shoot to root Ratio, RWC= relative water content, LA= leaf area, CC=chlorophyll content, EL= electrolytic leakage, PC= proline content, YPP= yield per plant (g)

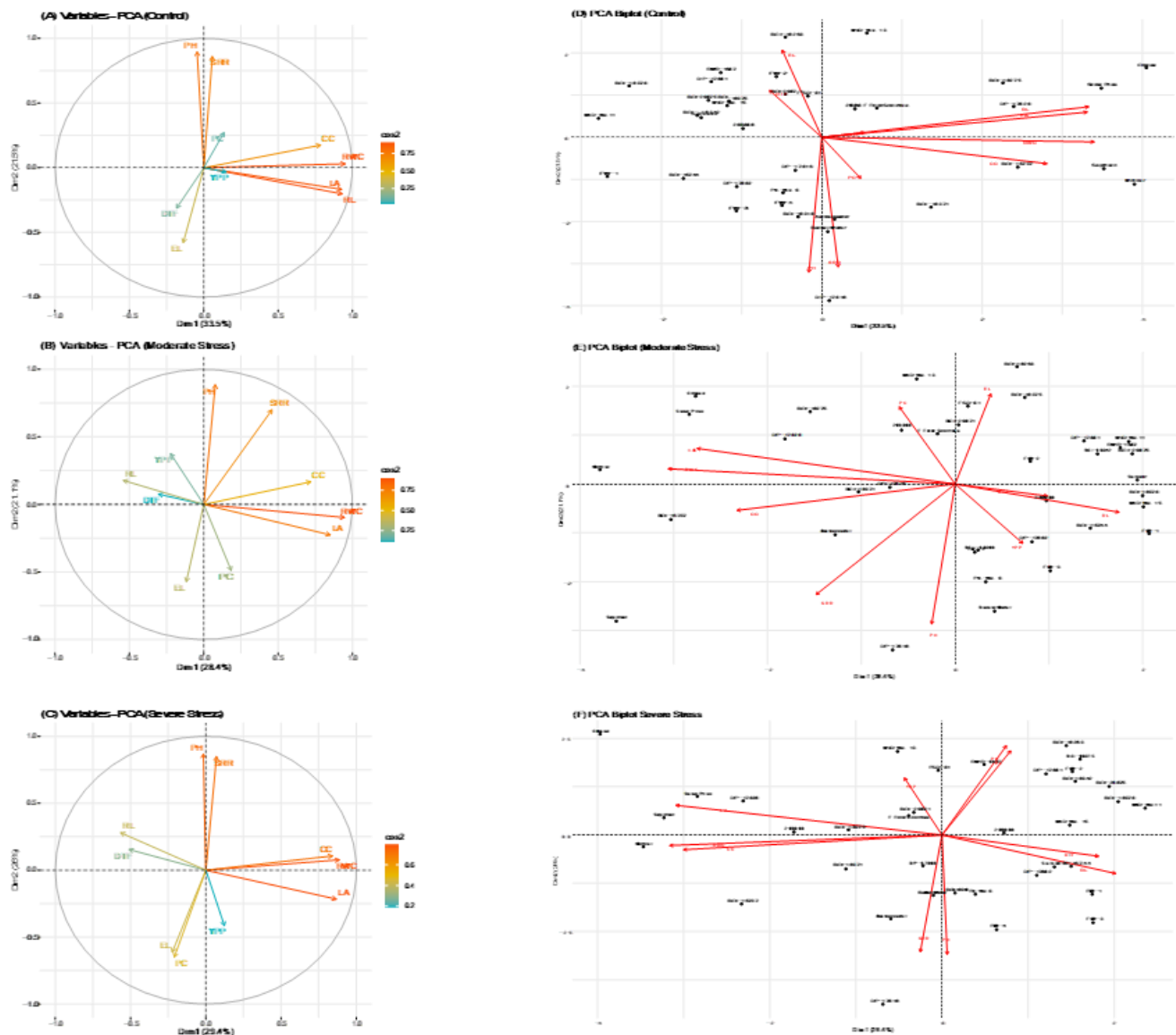


Figure 2: Principal component analysis of morpho-physiological traits and genotype distribution under control (A, D), moderate drought stress (B, E), and severe drought stress (C, F) conditions

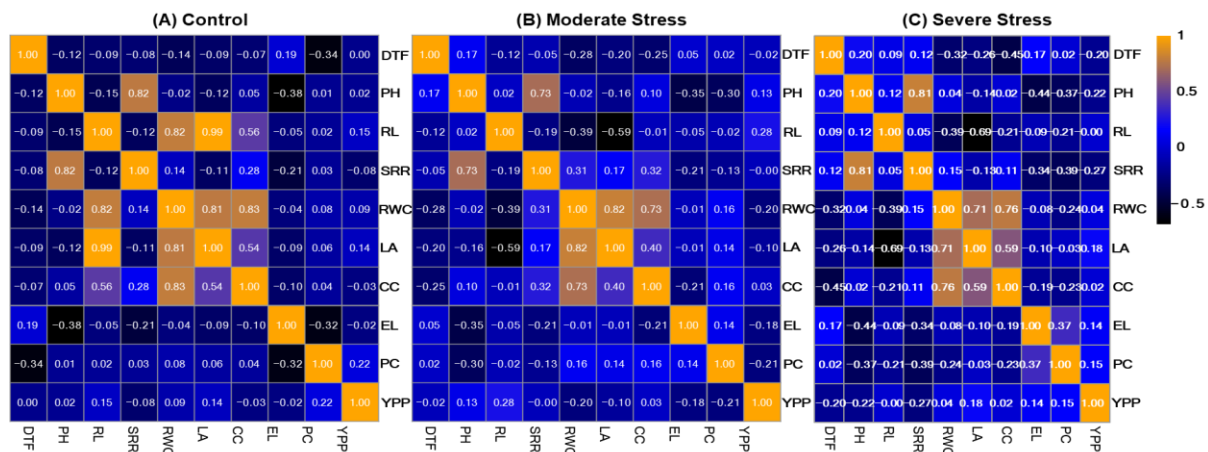


Figure 1: Pearson correlation heatmap of traits studied under the (A) control (B) moderate stress (C) severe stress.

The close correspondence between PCV and GCV under both moderate and severe stress conditions further suggests that phenotypic selection for these traits would be effective even under drought environments. High heritability coupled with high genetic advance for plant height, root length, relative water content, and chlorophyll content under control conditions indicates the predominance of additive gene action, suggesting that these traits can be effectively improved through direct selection. Under drought stress, the persistence of high variability and heritability for traits such as root length, electrolyte leakage, and relative water content highlights their critical role in drought adaptation. However, the reduction in heritability for certain traits under severe stress reflects increased environmental influence under extreme conditions. Yield per plant exhibited moderate heritability and genetic advance under stress, indicating that its improvement may require indirect selection through associated physiological traits. These results are consistent with previous findings in pea (6,18). They also reported that these key morphological and physiological traits exhibited high heritability and significant genetic variability. Principal component analysis (PCA) further emphasized the importance of physiological traits. The consistent contribution of RWC, CC, and LA across environments highlights their role as key determinants of drought tolerance. The negative loading of root length under stress conditions reflects adaptive plasticity. Moreover, root development plays an important role in water absorption under drought conditions. However, leaf area and chlorophyll content contribute to photosynthetic activity and biomass production. RWC reflects the ability of plants to maintain cellular hydration. Electrolyte leakage indicates greater membrane stability. The positive association among root length, leaf area, chlorophyll content, and relative water content was observed. It suggests that these traits help to improve drought tolerance and enhance stress tolerance in field pea.

Strong positive correlation among traits indicated that improved water conditions resulted in high photosynthetic efficiency and vegetative growth. The positive correlation of plant height with shoot-to-root ratio suggested coordinated growth under optimal conditions. In contrast, EC showed negative correlations with plant height and leaf area. This indicated that increased cellular damage adversely affects plant growth. Proline content (PC) showed a negative correlation with days to 50% flowering. This suggested its role in stress-induced phenological adjustments.

Plant height and root length maintained a strong positive relationship under moderate drought stress. This indicates coordinated shoot and root development under the water-limited environment. Relative water content also remained positively associated with chlorophyll content and leaf area. It emphasizes its importance in maintaining photosynthetic activity during water-stressed conditions.

Plant height remained positively correlated with the shoot-to-root ratio under severe drought stress. On the other hand, relative water content (RWC) continued to show positive relationships with chlorophyll content and leaf area. However, a negative correlation was observed between leaf area and root length. This suggests an exchange between

above- and below-ground growth under severe stress. Similarly, the negative association was observed between days to 50% flowering and chlorophyll content. This indicates stress-induced adjustments in plant development. These findings are consistent with a previous study of (19) on drought responses in pea.

The positive correlation between root traits and shoot-related traits under moderate stress was observed. It indicates that well-developed root systems enhance water uptake, thereby supporting plant growth. However, the weak association of yield with various traits under severe stress suggests that yield is a complex trait. It is governed by multiple interacting physiological and biochemical processes and environmental conditions. Therefore, direct selection of pea genotypes based on yield may be less effective under stress conditions. Moreover, the complexity of yield under stress conditions has also been reported in earlier studies (20,21).

Overall, the present study identifies plant height, root length, relative water content, chlorophyll content, and electrolyte leakage as reliable selection criteria for improving drought tolerance in field pea. Therefore, integration of these traits could significantly enhance the breeding programs for drought stress in peas.

Conclusion

Overall, the present study showed the presence of substantial genetic variability among pea genotypes for drought tolerance. Traits such as plant height, root length, relative water content, chlorophyll content, and electrolyte leakage consistently exhibited high heritability and genetic advance. This indicates the presence of additive gene action. Therefore, they have the potential to be considered as a reliable selection criterion in breeding programs. The study also shows that indirect selection through key physiological traits may be more effective for improving productivity under drought conditions than yield. This supports the integration of physiological traits into selection strategies for enhanced breeding efficiency. Although the present study provides valuable insight into drought tolerance mechanisms, it further needs validation under field conditions and integration of molecular approaches. Further studies will include the marker-assisted selection (MAS) for the selection of tolerant pea genotypes.

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contributed to data interpretation; M.T.A. contributed to scientific interpretation and critically reviewed the manuscript. All authors reviewed the manuscript.

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