



Assessment of morpho-physiological variability and yield potential in diverse pearl millet [*Pennisetum glaucum* (L.) R. Br.] germplasm across arid environments of Rajasthan

Jaishree Tanwar¹, C. Tara Satyavathi^{2*}, Ramesh¹, Supriya Ambawat³, Chandan Roy⁴, R. C. Meena⁵, Vikas Khandelwal⁶, Ravindra Kumar Meena⁷ and Preeti Devatwal³

<https://doi.org/10.37992/2026.1703.043>

Abstract

Pearl millet is a critical staple crop in the arid and semi-arid tropics, yet systematic characterization of genetic variability among diverse germplasm under multi-environment conditions remains limited. This study assessed genetic variability, heritability, genetic advance and trait associations among 300 diverse pearl millet genotypes evaluated across three locations for two years at Jodhpur, Nagaur and Bikaner during the *Kharif* seasons of 2022 and 2023. Twelve morphological and physiological traits were evaluated. Analysis of variance revealed highly significant genotypic variation across all traits, confirming substantial genetic variability in the germplasm. Grain yield per plant exhibited high heritability (80.0%) with a genetic advance of 48.1%, supporting the feasibility of yield improvement. Correlation analysis revealed strong positive associations of grain yield with dry panicle weight ($r=0.968$), 1000-seed weight ($r=0.992$) and chlorophyll content ($r=0.116$), identifying these as reliable selection criteria. These findings collectively establish a robust empirical basis for multi-trait selection incorporating both morphological and physiological parameters to accelerate genetic gains in pearl millet improvement programmes targeting stress-prone arid environments.

Keywords: Variability, Heritability, Correlation and Pearl millet

INTRODUCTION

Pearl millet [*Pennisetum glaucum* (L.) R. Br.], a cross-pollinated diploid ($2n = 14$) tropical C4 grass of the family Poaceae, is among the most stress-resilient cereal crops known, capable of sustaining productivity under drought, high temperatures, salinity, low soil fertility and adverse soil pH where other cereals fail entirely (Varshney *et al.*, 2017). In India, Rajasthan accounts for the largest share of pearl millet cultivation area, particularly in the A1 arid zone characterized by erratic rainfall below 400 mm, extreme temperatures, high evapotranspiration and sandy soils with poor water-holding capacity (AICSIP, 2022). Under these severe constraints, pearl millet often represents the only economically viable option for smallholder farmers. The diverse landraces and germplasm collections from such environments represent invaluable reservoirs of genetic variability encoding adaptive traits refined through millennia of natural and human selection under stress (Salgotra and Chauhan, 2023). Abiotic stresses collectively represent the most devastating constraints to global cereal productivity, with drought being the most pervasive, particularly in the arid and semi-arid systems where pearl millet is predominantly cultivated. Water deficit during flowering and grain filling severely impairs pollen viability, fertilization and assimilate supply, leading to dramatic yield reductions (Farooq *et al.*, 2009). The simultaneous occurrence of these stresses in farmers' fields underscores the complexity of breeding

¹Department of Genetics and Plant Breeding, Agriculture University, Jodhpur, Rajasthan, India

²Indian Institute of Millets Research, Hyderabad, Telangana, India

³Agriculture University, Jodhpur, Rajasthan, India

⁴Department of Genetics and Plant Breeding, School of Crop Improvement, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (I), Umiam, Meghalaya, India

⁵Sri Karan Narendra Agricultural University, Jobner, Rajasthan, India

⁶IIMR-Regional Research Station on Pearl millet, Gudamalani, Balotra, Rajasthan, India

⁷CCSHAU, Hisar, Haryana, India

Corresponding author: C. Tara Satyavathi, Indian Institute of Millets Research, Hyderabad, Telangana, India.

*E-Mail: csatyavathi@gmail.com

How to cite this article: Jaishree Tanwar, Tara Satyavathi, C., Ramesh, Supriya Ambawat, Chandan Roy, Meena, R. C., Vikas Khandelwal, Ravindra Kumar Meena and Preeti Devatwal: 2026. Assessment of morpho-physiological variability and yield potential in diverse pearl millet [*Pennisetum glaucum* (L.) R. Br.] germplasm across arid environments of Rajasthan. *Electronic Journal of Plant Breeding*, 17(3): 332-340.

doi:10.37992/2026.1703.043

Received: 03.06.2026 Revised: 16.09.2026 Accepted: 21.09.2026

for broad-spectrum stress tolerance and the imperative need for genotypes combining resilience with high yield potential. Pearl millet's inherent tolerance to stresses is mediated through diverse adaptive mechanisms, including deep root systems for enhanced moisture extraction, stomatal regulation to minimize transpiration loss, osmotic adjustment through accumulation of compatible solutes, and maintenance of membrane integrity and photosynthetic capacity under stress (Kholová *et al.*, 2012). Genotypes sustaining superior relative water content, membrane stability and chlorophyll content under stress have been consistently associated with enhanced productivity and resilience across diverse environments (Serba *et al.*, 2020).

Genetic variability is the cornerstone of any crop improvement programme, determining the scope and efficiency of selection (Allard, 1960). The genetic basis of stress tolerance in pearl millet is complex and quantitative, governed by numerous genes interacting significantly with the environment (Varshney *et al.*, 2017). Correlation analysis is indispensable for identifying such surrogate traits by quantifying the direction and magnitude of inter-trait associations (Dewey and Lu, 1959). Previous studies have highlighted the significance of panicle weight, panicle length, seed weight and stress-adaptive physiological traits as key contributors to grain yield in pearl millet (Serba *et al.*, 2020), yet systematic multi-environment characterization integrating both morphological and physiological traits in large, diverse germplasm panels under representative arid conditions remains limited.

MATERIALS AND METHODS

A core set of 300 diverse pearl millet genotypes (**Table 1**) representing various agro-ecological regions of India sourced from ICAR-All India Coordinated Research Project (AICRP) on Pearl Millet, Jodhpur, were evaluated at three locations, namely ICAR-AICRP on Pearl Millet, Jodhpur, Agricultural Research Sub-Station (ARSS), Nagaur and Agricultural Research Station (ARS), Bikaner in *Kharif* season of year 2022 and 2023. Climatically, all locations fall within the Arid Western Plains Zone of Rajasthan, receiving 260–400 mm annual rainfall, of which 85–90 per cent occurs during June–September (**Table 2 - 4**). The trials were performed in a randomized block design (RBD) with 3 replications. Each genotype was sown in 2 rows of 2 m length across three locations. Recommended agronomic practices for rainfed pearl millet were followed uniformly across all locations.

Data were recorded on five randomly selected plants per replication for all traits, except days to 50% flowering, which was recorded on a plot basis. Days to 50% flowering was measured as the number of days from sowing to 50% stigma emergence in the inflorescence. Panicle length (cm) and panicle thickness (cm) were measured at dough grain stage using a digital Vernier calliper. Thousand-seed weight (g) was estimated by weighing a subsample of 250

seeds from each replication and converting the value to a 1000-seed basis. Grain yield per plant (g) was obtained by threshing five tagged plants together. Dry panicle weight (g) and post-threshing panicle weight (g) were recorded after oven-drying at 70°C for 72 h. Relative water content (%) was determined using the third fully expanded leaf from the top of the plant at the seedling stage using fresh (FW), turgid (TW, after 24 h rehydration) and dry weights (DW, 70°C for 48 h) as $RWC = [(FW - DW) / (TW - DW)] \times 100$ (Slavik, 1974). Membrane stability index (%) was computed from electrical conductivity of 0.1 g leaf tissue in distilled water at 40°C for 30 min (C_1) and 100°C for 10 min (C_2) as $MSI = [1 - (C_1/C_2)] \times 100$ (Sairam, 1994). Chlorophyll content (mg g⁻¹ FW) was determined spectrophotometrically at 663 and 645 nm from 80% acetone extracts of 0.1 g leaf tissue (Arnon, 1949); SPAD-502 meter readings were also recorded at the seedling stage. Flag leaf area (FLA, cm²) was estimated as $FLA = 0.68 \times (L \times W) - 0.114$ (Payne *et al.*, 1991), where L and W are flag leaf length and maximum width (cm) measured after panicle emergence.

Data were subjected to analysis of variance (ANOVA) to partition the total variation into components attributable to genotypes, environments, and their interactions, following the model explained by (Panse and Sukhatme, 1985). Genetic parameters, including genotypic and phenotypic coefficients of variation (GCV, PCV), were measured according to (Burton and de Vane, 1953). Broad-sense heritability (h^2_{bs}) and genetic advance (GA) as a percentage of the mean (at 5% selection intensity) were calculated following (Johnson *et al.*, 1955). The phenotypic, genotypic and environmental coefficients of correlation were calculated as per (Al-jibouri *et al.*, 1958). All analyses were performed using the *agricolae* and *variability* packages in R software (version 4.5.1; R Core Team, 2024).

RESULTS AND DISCUSSION

Genetic variability, heritability and genetic advance

The assessment of genetic variability constitutes a foundational step in any crop improvement program, as it determines the scope and effectiveness of selection (Falconer and Mackay, 1996). Analysis of variance (**Table 5**) revealed highly significant mean sum of squares for all traits evaluated *i.e.*, days to 50% flowering, panicle length, panicle thickness, weight of panicle after threshing, dry weight of panicle, thousand seed weight, relative water content, SPAD value, flag leaf area, chlorophyll content, membrane stability index and grain yield per plant confirming the presence of substantial genetic diversity among the 300 genotypes. PCV values were consistently higher than corresponding GCV values across most traits, confirming that environmental factors contributed measurably to phenotypic expression, a pattern widely documented in pearl millet and related cereals (Hasan-Ud-Daula *et al.*, 2020) (**Table 6**). High to moderate GCV and PCV values were recorded for panicle length (22.6 and 22.8 %), dry weight of panicle (21.5 and

Table 1. List of pearl millet genotypes screened for analysis

S.No.	Identity	S.No.	Identity	S.No.	Identity	S.No.	Identity	S.No.	Identity
G1	IC-102797	G61	NBPGR-37	G121	NIC-17770	G181	IC-537958	G241	Kajoi-8
G2	IC-139869	G62	NBPGR-38	G122	NIC-17772	G182	IC-537960	G242	Shergarh-3
G3	IC-329041	G63	NBPGR-39	G123	NIC-17783	G183	IC-537962	G243	Shergarh-4
G4	IC-332703	G64	NBPGR-45	G124	NIC-17785	G184	IC-537984	G244	Shergarh-5
G5	IC-332706	G65	NBPGR-52	G125	NIC-17830	G185	IC-537953	G245	Shergarh-6
G6	IC-332707	G66	NBPGR-60	G126	NIC-17831	G186	IC-329053	G246	Kapoordi-1
G7	IC-332715	G67	NBPGR-61	G127	NIC-17834	G187	IC-420367	G247	Kapoordi-2
G8	IC-332716	G68	NBPGR-64	G128	NIC-17806	G188	IC-449431	G248	Kapoordi-5
G9	IC-332725	G69	NBPGR-65	G129	NIC-17807	G189	IC-449438	G249	Kapoordi-6
G10	IC-332726	G70	NBPGR-70	G130	NIC-17808	G190	IC-449442	G250	Agolai-1
G11	IC-332727	G71	MBC 2	G131	NIC-17809	G191	IC-449443	G251	Agolai-2
G12	IC-332733	G72	NBPGR-72	G132	NIC-17811	G192	IC-449444	G252	Agolai-3
G13	IC-332742	G73	NBPGR-73	G133	NIC-17812	G193	IC-449456	G253	Agolai-4
G14	IC-102804	G74	NBPGR-76	G134	NIC-17815	G194	IC-449466	G254	Agolai-5
G15	IC-325785	G75	NBPGR-91	G135	NIC-17818	G195	IC-449469	G255	Agolai-6
G16	IC-325786	G76	NBPGR-92	G136	IC-323993	G196	IC-449485	G256	Agolai-7
G17	IC-373424	G77	NBPGR-106	G137	IC-325179	G197	IC-53762	G257	Agolai-9
G18	IC-373431	G78	NBPGR-110	G138	IC-325765	G198	IC-541016	G258	Agolai-10
G19	IC-370501	G79	NBPGR-115	G139	IC-325815	G199	IC-541020	G259	Agolai-11
G20	IC-139909	G80	NBPGR-116	G140	IC-329042	G200	IC-516582	G260	Agolai-12
G21	IC-139915	G81	NBPGR-117	G141	IC-329043	G201	IC-537953	G261	Agolai-13
G22	IC-139914	G82	NBPGR-122	G142	IC-329045	G202	IC-537961	G262	Kansar-1
G23	IC-139916	G83	NBPGR-123	G143	IC-329047	G203	IC-537980	G263	Kansar-2
G24	IC-139917	G84	NBPGR-129	G144	IC-329052	G204	IC-537984	G264	Kansar-3
G25	IC-139919	G85	NBPGR-131	G145	IC-329054	G205	IC-537985	G265	Ghantiyala-1
G26	IC-139922	G86	NBPGR-133	G146	IC-329056	G206	IC-537991	G266	Ghantiyala-2
G27	IC-139928	G87	NBPGR-135	G147	IC-329068	G207	IC-537993	G267	Ghantiyala-3
G28	IC-370481	G88	NBPGR-136	G148	IC-329069	G208	IC-541023	G268	Ghantiyala-4
G29	IC-370522	G89	NBPGR-176	G149	IC-329072	G209	IC-285200	G269	Ghantiyala-5
G30	IC-370523	G90	NBPGR-181	G150	IC-329074	G210	IC-420330	G270	Ghantiyala-6
G31	IC-370524	G91	NBPGR-182	G151	IC-373558	G211	IC-537967	G271	Ghantiyala-7
G32	IC-557624	G92	NBPGR-188	G152	530 k/18	G212	3	G272	Balesar-1
G33	IC-557625	G93	NBPGR-191	G153	540 k/18	G213	11	G273	Balesar-4
G34	IC-557630	G94	NBPGR-194	G154	541 k/18	G214	16	G274	Balesar-5
G35	IC-557636	G95	NBPGR-195	G155	543-549 k /18	G215	18	G275	Balesar-6
G36	IC-557637	G96	NBPGR-197	G156	550-55 k/18	G216	CZP9802	G276	Balesar-7
G37	IC-139898	G97	NBPGR-198	G157	565-569 k/18	G217	CZP IC 923	G277	Balesar-8
G38	IC-139899	G98	NBPGR-210	G158	571-572 k/18	G218	Sulkhaniya Bajri	G278	Balesar-9
G39	IC-139900	G99	NBPGR-213	G159	576-577 k/18	G219	Kawas-1	G279	GSP Shergarh-1
G40	IC-139903	G100	NBPGR-214	G160	BBNH 0601-7	G220	Kawas-2	G280	GSP Shergarh-2
G41	IC-139904	G101	NBPGR-221	G161	BBNH0601-8-2	G221	Kawas-3	G281	GSP Shergarh-3
G42	IC-139906	G102	NBPGR-222	G162	BBNH0601-11	G222	Kawas-4	G282	GSP Shergarh-4
G43	IC-139930	G103	NBPGR-224	G163	BBNH0601-15	G223	Kawas-5	G283	GSP Shergarh-5
G44	IC-139932	G104	NBPGR-226	G164	BBNH0601-16	G224	Kawas-6	G284	GSP Shergarh-6
G45	IC-370720	G105	NBPGR-227	G165	401-SB-19	G225	Kawas-7	G285	GSP Shergarh-7
G46	ArdiDungri ka bas	G106	NBPGR-228	G166	J-2526	G226	Kanor Shiv-1	G286	GSP Shergarh-8
G47	Ardi BKB	G107	NBPGR-229	G167	J-2563	G227	Kanor Shiv-2	G287	OR Ghantiyala-1
G48	BikaneriBajri Jodhasar	G108	NBPGR-234	G168	J-2579	G228	Kanor Shiv-3	G288	OR Ghantiyala-2
G49	Chadi Bristle	G109	NBPGR-235	G169	J-2584	G229	Kanor Shiv-4	G289	OR Ghantiyala-3
G50	Desi Panchu	G110	NBPGR-238	G170	J-2621	G230	Baytu-3	G290	OR Ghantiyala-4
G51	DhodsarLocal original	G111	NBPGR-241	G171	172-SB-19	G231	Baytu-6	G291	OR Ghantiyala-5
G52	Desi Karnu SPS	G112	NBPGR-992	G172	175-SB-19	G232	Baytu-7	G292	OR Ghantiyala-6
G53	Desi Osian	G113	NBPGR-993	G173	IC-285200	G233	Baytu-8	G293	OR Ghantiyala-7
G54	Jhukarana Local	G114	NBPGR-996	G174	IC-333179	G234	Kansar Shiv-1	G294	OR Ghantiyala-8
G55	NKD/YSR-2936	G115	NBPGR-998	G175	IC-420336	G235	Kansar Shiv-2	G295	SR Ghantiyala-1
G56	SulkhunaLocal(SR)	G116	NBPGR-9913	G176	IC-420347	G236	Kansar Shiv-3	G296	SR Ghantiyala-2
G57	Thakarana	G117	NBPGR-9915	G177	IC-420352	G237	Kansar Shiv-4	G297	SR Ghantiyala-3
G58	NBPGR-34	G118	NBPGR-9928	G178	IC-420360	G238	Kansar Shiv-6	G298	SR Ghantiyala-4
G59	NBPGR-35	G119	NIC-17762	G179	IC-420371	G239	Kajoi-3	G299	SR Ghantiyala-5
G60	NBPGR-36	G120	NIC-17769	G180	IC-537954	G240	Kajoi-6	G300	SR Ghantiyala-6

Table 2. Meteorological data record during *Kharif* season of 2022 and 2023 at Jodhpur

Standard week	Meteorological week	Temperature (°C)				Rainfall (mm)		Number of rainy days		Relative humidity (%)			
		Maximum		Minimum		2022	2023	2022	2023	Maximum		Minimum	
		2022	2023	2022	2023					2022	2023	2022	2023
28	9July–15July	38.0	34.1	25.4	27.1	7.0	20.1	0.0	2.0	76.3	84.0	64.9	69.1
29	16July–22July	36.6	36.8	25.3	27.6	29.0	69.1	2.0	2.0	71.0	81.9	60.0	58.7
30	23July–29July	33.8	34.6	24.7	27.3	47.5	39.3	3.0	2.0	79.7	86.1	66.7	62.1
31	30July–5 Aug.	32.0	33.0	24.1	26.4	4.0	0.0	0.0	0.0	68.4	88.9	55.7	57.0
32	6Aug–12Aug.	32.2	33.3	22.7	25.4	78.2	0.0	3.0	0.0	75.2	81.3	55.2	55.3
33	13Aug–19Aug.	31.8	33.7	21.5	25.7	74.3	0.0	4.0	0.0	87.3	81.1	71.1	52.3
34	20Aug–26Aug	29.2	34.3	20.5	25.6	48.0	8.3	4.0	0.0	85.8	80.6	71.1	54.0
35	27Aug–2 Sept.	32.9	34.5	21.4	26.2	0.0	0.0	1.0	0.0	71.4	72.0	53.3	43.3
36	3Sept–9Sept.	36.0	38.0	21.4	26.5	0.0	0.0	0.0	0.0	70.3	65.9	45.2	35.9
37	10Sept–16Sept	36.4	36.2	22.1	26.5	32.0	41.5	3.0	1.0	71.9	78.7	53.3	51.0
38	17Sept–23Sept.	35.0	33.5	22.7	25.8	0.0	13.4	0.0	2.0	70.6	88.3	49.5	60.1
39	24Sept–30Sept.	39.3	37.0	21.1	25.6	26.2	0.0	4.0	0.0	68.5	79.6	50.8	39.0
40	01Oct–07Oct	34.4	37.1	21.1	22.4	0.0	0.0	0.0	0.0	64.2	65.0	57.0	40.1
41	08Oct–14Oct	38.2	33.9	26.4	21.9	52.0	0.0	4.0	0.0	70.4	66.3	61.9	38.3

Table 3. Meteorological data record during *Kharif* season of 2022 and 2023 at Bikaner

Standard week	Meteorological week	Temperature (°C)				Rainfall (mm)		Number of rainy days		Relative humidity (%)			
		Maximum		Minimum		2022	2023	2022	2023	Maximum		Minimum	
		2022	2023	2022	2023					2022	2023	2022	2023
28	9July–15July	36.0	37.9	25.5	25.7	89.1	127.6	5.0	1.0	85.3	80.6	68.4	49.7
29	16July–22July	35.2	37.7	25.1	25.9	80.2	35.8	3.0	3.0	86.7	80.3	61.3	55.9
30	23July–29July	33.5	34.9	25.4	25.2	28.4	47.6	3.0	3.0	91.3	88.7	71.4	67.7
31	30July–5 Aug.	35.8	35.9	25.7	25.5	2.2	0.2	0.0	0.0	81.7	82.9	61.6	54.6
32	6Aug–12Aug.	36.0	35.2	25.8	25.3	12.0	0.0	3.0	0.0	84.9	77.1	55.0	49.7
33	13Aug–19Aug.	33.0	36.4	23.8	25.3	17.8	0.0	2.0	0.0	89.0	75.6	68.6	47.1
34	20Aug–26Aug	34.4	36.6	23.9	25.8	1.2	0.0	0.0	0.0	83.9	77.4	58.6	46.3
35	27Aug–2 Sept.	36.8	37.1	24.1	24.8	8.2	0.0	1.0	0.0	76.7	69.7	45.4	40.1
36	3Sept–9Sept.	37.7	39.2	24.1	25.3	0.0	0.0	0.0	0.0	73.3	68.1	42.7	34.6
37	10Sept–16Sept	38.1	38.9	24.6	26.0	0.4	20.0	0.0	1.0	77.0	72.6	47.7	44.7
38	17Sept–23Sept.	37.2	34.7	22.9	24.5	0.8	41.8	0.0	2.0	76.9	84.3	45.9	65.3
39	24Sept–30Sept.	37.6	37.5	22.2	23.9	0.0	0.0	0.0	0.0	70.3	75.3	38.4	44.0
40	01Oct–07Oct	37.6	37.6	19.8	20.2	0.0	0.0	0.0	0.0	66.7	62.0	33.0	36.7
41	08Oct–14Oct	34.2	37.0	19.3	21.6	0.0	0.0	0.0	0.0	80.1	69.9	43.4	33.4

21.7 %), relative water content (14.2 and 14.3 %) and membrane stability index (15.4 and 15.6 %), indicating strong additive gene action and high selection efficiency. Comparable findings have been reported by Annamalai *et al.* (2020) and Singh and Chhabra (2018) for flag leaf area; Yadav *et al.* (2021) for panicle length; and Arunachalam *et al.* (2022) for membrane stability index and relative water content in sorghum. High h^2 bs (Table 6) was recorded for the majority of traits, indicating that a preponderant share of phenotypic variance was of genetic origin consistent

with earlier variability studies in pearl millet (Sathya *et al.*, 2014; Singh and Chhabra, 2018). Relative water content recorded very high heritability (99.0 %) with genetic advance 38.3 %; Chlorophyll content showed high heritability 98.0 %; membrane stability index exhibited 99.0 % heritability with genetic advance as percent mean of 34.8–66.4 % in various environments reflecting strong genetic control and suitability for stress tolerance breeding. SPAD value also exhibited high heritability (98.0 %) with genetic advance of 57.0%, supporting its

reliability as a physiological selection criterion. Flag leaf area recorded 99.0 % heritability with genetic advance of 49.2%, indicating substantial scope for phenotypic selection. Days to 50% flowering recorded GCV and PCV values of 5.6 and 5.7 %, respectively, with high heritability (97.0 %) and genetic advance of 11.4 % in pooled data,

suggesting effective selection for earliness. Similar low estimates of GCV and PCV were reported by (Sowmiya *et al.*, 2016) in pearl millet for days to 50% flowering. Further, Patel *et al.* (2019) and Narasimhulu *et al.* (2021) in pearl millet reported similar findings for flowering and maturity traits, indicating relatively narrow genetic variability.

Table 4. Meteorological data record during *Kharif* season of 2022 and 2023 at Nagaur

Standard week	Meteorological week	Mean temperature (°C)		Rainfall (mm)	
		2022	2023	2022	2023
28	9July–15July	31.5	31.5	49.99	43.24
29	16July–22July	31.5	31.5	49.99	43.24
30	23July–29July	31.5	31.5	49.99	43.24
31	30July–5Aug.	29.7	29.7	40.49	13.63
32	6Aug–12Aug.	29.0	29.0	36.69	1.78
33	13Aug–19Aug.	29.0	29.0	36.69	1.78
34	20Aug–26Aug	29.0	29.0	36.69	1.78
35	27Aug–2Sept.	29.1	29.1	27.46	4.61
36	3Sept–9 Sept.	29.5	29.5	4.36	11.67
37	10Sept–16 Sept	29.5	29.5	4.36	11.67
38	17Sept–23 Sept.	29.5	29.5	4.36	11.67
39	24Sept–30 Sept.	29.5	29.5	4.36	11.67
40	01Oct–07Oct	27.5	27.5	1.13	1.13
41	08Oct–14Oct	27.5	27.5	1.13	1.13

Table 5. Analysis of variance for yield and its contributing traits for different locations

Location	Trait	PL	DWP	WP	GYP	RWC	SPAD	MSI	CC	FLA	DFF	PT	TSW
JODHPUR 22	REP	4.7	0.4	5.3	0.1	7.5	6.7	2.7	0.1	16.2	0.7	0.1	0.7
	GEN	71.9*	101.8*	70.8*	3.8*	295.9*	566.8*	355.8*	2.1*	645.5*	26.1*	0.4*	3.2*
	Error	1.7	4.2	3.8	0.1	3.0	8.5	0.2	0.1	8.6	0.2	0.1	0.1
JODHPUR 23	REP	2.8	1.0	4.6	0.1	7.5	19.2	2.9	0.1	16.2	0.7	0.1	0.7
	GEN	74.6*	101.6*	70.8*	3.8*	341.2*	2277.8*	374.1*	2.1*	662.5*	26.0*	0.5*	3.4*
	Error	1.0	4.7	4.3	0.1	3.0	32.6	1.0	0.1	8.6	0.2	0.1	0.1
BIKANER 22	REP	3.3	7.8	0.8	0.1	2.9	6.9	0.1	0.1	6.0	2.9	0.1	0.1
	GEN	57.6*	104.6*	79.7*	2.8*	290.6*	531.1*	383.1*	2.3*	643.2*	28.6*	0.5*	2.8*
	Error	1.6	2.8	1.9	0.1	1.2	8.4	0.1	0.1	2.3	1.5	0.1	0.1
BIKANER 23	REP	4.4	9.2	9.2	0.1	2.9	19.4	0.1	0.1	6.0	2.9	0.1	0.1
	GEN	57.6*	104.0*	79.6*	2.8*	363.8*	2124.6*	379.4*	2.3*	669.6*	19.4*	0.6*	3.20*
	Error	1.5	3.1	3.7	0.1	1.2	36.4	1.7	0.1	2.3	1.4	0.1	0.1
NAGAUUR 22	REP	3.3	6.8	8.3	0.1	6.0	0.8	0.5	0.1	0.8	0.7	0.1	0.1
	GEN	57.5*	81.5*	61.2*	1.9*	320.3*	541.4*	376.9*	2.3*	661.8*	28.7*	0.4*	3.3*
	Error	1.6	4.1	3.0	0.1	2.1	10.1	0.2	0.1	0.5	0.4	0.1	0.1
NAGAUUR 23	REP	1.4	12.0	1.1	0.1	6.0	8.7	3.0	0.1	0.8	0.7	0.1	0.1
	GEN	67.3*	81.4*	61.2*	0.5*	320.3*	2165.0*	378.0*	2.3*	656.0*	19.8*	0.4*	3.3*
	Error	0.8	4.9	2.5	0.1	2.1	38.2	1.0	0.1	0.5	0.4	0.1	0.1

*Significance at 5% level

Where PL: Panicle length, DWP: Dry weight of panicle, WP: weight of panicle, GYP: Grain yield per plant, RWC: Relative water content, SPAD: soil and plant analysis development, MSI: Membrane stability index, CC: chlorophyll content, FLA: Flag leaf area, DFF: Days to 50% flowering, PT: Panicle Thickness, TSW: Thousand seed weight.

Table 6. Genetic variability parameters for yield and its contributing traits for different locations

Environment	Parameter	PL	DWP	WP	DFF	PT	TSW	RWC	CC	SPAD	MSI	FLA	GYP
JODHPUR-22	GCV(%)	22.7	22.1	21.5	6.7	16.2	17.6	12.9	42.5	24.5	12.7	27.6	14.5
	PCV(%)	23.5	23.5	23.3	6.8	16.3	18.0	13.1	43.4	25.2	12.7	28.2	14.5
	H ² (%)	93.0	88.6	85.5	97.2	98.8	96.8	97.0	95.7	94.5	99.0	96.1	99.1
	Mean	21.3	25.8	21.9	43.4	2.4	5.8	76.1	2.0	55.9	85.5	52.6	7.7
	GAM(%)	45.3	38.2	37.2	13.8	34.2	34.8	33.6	77.7	60.1	34.8	46.3	28.5
JODHPUR-23	GCV(%)	23.3	22.0	21.5	6.0	31.6	31.0	15.5	61.1	24.4	20.4	30.7	66.1
	PCV(%)	23.7	23.6	23.0	6.1	31.7	32.1	15.7	62.8	25.0	20.4	31.3	66.4
	H ² (%)	96	87.3	83.0	97.2	99.0	97.0	97.4	95.0	95.6	99.2	96.2	99.1
	Mean	21.1	25.8	21.9	48.4	1.4	3.3	68.2	1.4	55.7	55.7	48.0	1.7
	GAM(%)	56.7	37.8	36.7	12.3	48.6	54.1	43.5	90.1	60.2	66.4	50.2	35.6
BIKANER-22	GCV(%)	21.9	23.2	26.0	6.7	16.6	19.2	12.8	42.8	22.8	13.6	26.9	18.3
	PCV(%)	22.9	24.2	27.9	7.3	16.7	19.4	12.9	43.0	23.5	13.6	27.1	18.4
	H ² (%)	92.1	92.5	84.2	86.2	99.0	98.5	98.7	98.1	94.3	99.1	98.0	98.8
	Mean	19.7	25.0	22.4	44.6	2.5	5.0	76.7	2.1	57.7	82.8	54.1	5.3
	GAM(%)	47.5	49.4	45.3	13.4	29.1	36.8	34.2	81.2	52.5	38.1	46.1	34.5
BIKANER-23	GCV(%)	22.0	23.1	22.4	4.8	39.6	29.9	16.1	69.7	22.8	18.9	32.3	29.5
	PCV(%)	22.8	24.2	24.0	5.3	39.8	30.0	16.2	70.1	23.4	19.0	32.4	29.7
	H ² (%)	92.5	91.5	87.2	80.5	99.1	98.6	98.9	98.1	95.4	98.6	98.0	98.8
	Mean	19.7	25.0	22.4	50.6	1.1	3.4	68.0	1.3	57.7	59.3	46.1	3.13
	GAM(%)	49.0	48.9	41.2	8.9	85.2	55.7	44.3	92.3	52.9	60.8	53.7	53.1
NAGAU-22	GCV(%)	23.6	20.2	19.8	6.6	13.1	20.0	14.1	47.2	25.9	14.2	27.8	21.2
	PCV(%)	24.0	21.8	21.3	6.8	13.2	20.3	14.3	47.5	26.6	14.2	27.9	21.7
	H ² (%)	96.7	86.1	86.7	96.2	98.4	96.9	98.0	98.6	94.9	99.8	99.0	95.9
	Mean	19.9	25.1	22.2	46.7	2.7	5.2	72.8	1.9	51.3	78.8	53.2	3.7
	GAM(%)	54.7	34.8	34.0	13.7	25.0	38.1	38.1	88.7	62.6	40.2	49.0	38.5
NAGAU-23	GCV(%)	23.0	20.1	19.9	5.0	36.3	32.7	14.5	60.2	25.9	15.8	31.3	32.2
	PCV(%)	24.0	21.9	21.1	5.1	36.6	33.3	14.7	60.1	26.6	15.9	31.3	34.7
	H ² (%)	96.5	84	88.7	94.5	98.4	96.5	98.0	98.6	94.5	99.2	99.0	86.7
	Mean	19.9	25.1	22.2	50.7	1.0	3.2	70.8	1.5	51.3	70.5	47.2	1.2
	GAM(%)	54.6	34.1	34.6	9.9	62.2	59.8	39.5	89.5	62.5	46.6	50.4	52.8
POOLED	GCV(%)	22.6	21.5	21.1	5.6	19.1	23.0	14.2	51.7	23.4	15.4	29.2	23.3
	PCV(%)	22.8	21.7	21.5	5.7	19.0	23.1	14.3	52.1	23.7	15.6	29.3	23.4
	H ² (%)	98.1	97.5	97.0	97.2	99.6	99.3	99.6	98.4	98.0	99.8	99.1	99.5
	Mean	21.1	25.3	22.7	47.4	1.8	4.3	72.1	1.7	54.9	72.1	50.2	3.8
	GAM(%)	51.0	41.3	39.6	11.4	35.2	43.4	38.3	95.0	57.0	45.2	49.2	43.6

Where, PL: Panicle length, DWP: Dry weight of panicle, WP: weight of panicle, DFF: Days to 50% flowering, PT: Panicle Thickness, TSW: Thousand seed weight, RWC: Relative water content, CC: chlorophyll content, SPAD: soil and plant analysis development, MSI: Membrane stability index, FLA: Flag leaf area, GYP: Grain yield per plant.

Panicle length showed pooled GCV and PCV values of 22.6 % and 22.8 %, with high heritability (98.0 %) coupled with high genetic advance of 51.0 %, reflecting strong genetic control and high selection efficiency. Dry weight of panicle exhibited GCV and PCV of 21.5 and 21.7 %, heritability of 97.0 % coupled with high genetic advance of 41.3 %, indicating substantial additive genetic effects. Weight of panicle after threshing recorded GCV and PCV values of 11.1 and 21.5% high heritability (97.0%)

and genetic advance reaching 39.6 %, demonstrating good potential for improvement. Panicle thickness showed GCV and PCV values (19.1 %), high heritability (99.0 %) with genetic advance of 35.2 %, indicating minimal environmental influence and strong genetic determination. Thousand seed weight exhibited GCV and PCV values of 23.1 %, heritability of 99.0 % and genetic advance of 43.4 %, highlighting excellent prospects for selection. Grain yield per plant displayed GCV (23.3 %)

and PCV (23.4 %), maintaining high heritability (99.0 %) and genetic advance as percent of mean of 43.6 %, suggesting that yield improvement can be effectively achieved through selection. Hence, exhibited a pattern suggestive of non-additive gene effects, epistasis or genotype $\times$ environment interactions, cautioning against sole reliance on phenotypic selection for this trait (Sathya *et al.*, 2014). Overall, the predominance of high heritability coupled with moderate-to-high genetic advance across traits confirms the preponderance of additive genetic control, while underscoring the complexity of inheritance in phenological characters under variable environments. The very high heritability estimates are attributable to the broad genetic base of the population maximizing genotypic variance relative to environmental variance (Falconer and Mackay, 1996), and to the inherently buffered nature of physiological traits such as relative water content, membrane stability index and SPAD against micro-environmental perturbations, thereby sustaining consistently low variation across environments (Farooq *et al.*, 2009).

Correlation among physiological and yield traits

Correlation analysis (**Table 7**) serves as an indispensable tool in plant breeding, elucidating the direction and magnitude of associations among traits and thereby identifying secondary characters that can serve as reliable surrogates for direct selection of complex, low-heritability traits (Dewey and Lu, 1959). A consistent observation in the present study was that genotypic correlation coefficients exceeded their phenotypic counterparts for most trait pairs, indicating that intrinsic genetic associations are stronger than those expressed at the phenotypic level, where environmental noise tends to obscure true biological relationships a finding well corroborated in pearl millet and allied cereal crops (Reddy *et al.*, 2013). Grain yield per plant exhibited positive and highly significant correlations at both genotypic and phenotypic levels with panicle length ($r = 0.103$), dry weight of panicle ($r = 0.968$), 1000-grain weight ($r = 0.992$) (Vetriventhan and Nirmalakumari, 2007), panicle thickness ($r = 0.275$), chlorophyll content ($r = 0.116$) and weight of panicle after threshing ($r = 0.966$). The particularly strong associations

Table 7. Genotypic and phenotypic correlation coefficient of various traits

Trait		PL	DWP	WP	GYP	RWC	SPAD	MSI	CC	FLA	DFF	PT	TSW
PL	G	1.000	0.094	0.115*	0.103	0.034	0.020	-0.075	0.004	0.048	0.179**	0.128*	0.130*
	P	1.000	0.094**	0.113**	0.103**	0.034	0.018	-0.075*	0.004	0.047	0.175**	0.126**	0.129**
DWP	G		1.000	0.993**	0.968**	-0.074	-0.072	0.010	0.103	-0.017	0.082	0.284**	0.960**
	P		1.000	0.983**	0.959**	-0.073*	-0.073*	0.009	0.102**	-0.017	0.079*	0.281**	0.950**
WP	G			1.000	0.966**	-0.063	-0.055	0.014	0.100	-0.017	0.080	0.289**	0.961**
	P			1.000	0.956**	-0.062	-0.053	0.014	0.100**	-0.018	0.079*	0.286**	0.949**
GYP	G				1.000	-0.082	-0.040	0.005	0.116*	-0.023	0.060	0.275**	0.992**
	P				1.000	-0.081*	-0.040	0.005	0.116**	-0.024	0.059	0.274**	0.988**
RWC	G					1.000	0.011	0.243**	-0.335**	0.040	0.071	0.020	-0.074
	P					1.000	0.011	0.242**	-0.333**	0.040	0.071*	0.020	-0.074*
SPAD	G						1.000	-0.092	0.006	-0.045	-0.179**	0.030	-0.035
	P						1.000	-0.091**	0.007	-0.045	-0.174**	0.030	-0.035
MSI	G							1.000	-0.062	0.068	0.137*	0.070	0.021
	P							1.000	-0.062	0.068*	0.136**	0.070*	0.022
CC	G								1.000	-0.053	-0.066	-0.078	0.122*
	P								1.000	-0.053	-0.064	-0.077*	0.122**
FLA	G									1.000	0.148*	-0.105	-0.014
	P									1.000	0.146**	-0.104**	-0.013
DFF	G										1.000	0.084	0.060
	P										1.000	0.083*	0.059
PT	G											1.000	0.286**
	P											1.000	0.284**
TSW	G												1.000
	P												1.000

**Significance at 1% level; * Significant at 5% level

Where PL: Panicle length, DWP: Dry weight of panicle, WP: weight of panicle, GYP: Grain yield per plant, RWC: Relative water content, SPAD: soil and plant analysis development, MSI: Membrane stability index, CC: chlorophyll content, FLA: Flag leaf area, DFF: Days to 50% flowering, PT: Panicle Thickness, TSW: Thousand seed weight.

Table 8. List of morphological trait wise promising genotypes on basis of pooled data

Trait	Genotypes (Mean)
Panicle length	Kawas-2 (40.27), SR Gantiyala-4 (38.06), Kawas-3 (36.45)
Dry weight of panicle	IC-370523 (59.95), IC-102804 (55.08), IC-373431 (52.98)
Weight of panicle after threshing	IC-370523 (50.72), IC-102804 (47.8), IC-373431 (45.09)
Grain yield per plant	IC-370523 (8.65), IC-373431 (8.29), IC-102804 (8.16)
Flag leaf area	Ghantiyala-4 (95.95), Kawas-6 (88.04), Chadi Bristle (87.98)
Days to 50% flowering	NBPGR-116 (41.52), MBC 2 (41.61), NBPGR-60 (41.63)
Panicle thickness	J-2563 (2.98), J-2584 (2.84), 175-SB-19 (2.64)
Thousand seed weight	IC-370523 (9.06), IC-373431 (8.89), IC-102804 (8.76)

between yield and panicle-related traits, dry panicle weight and post-threshing panicle weight, indicate that these characteristics are not merely correlated with yield but likely represent key determinants of overall productivity, making them effective targets for indirect selection. The use of morphologically measurable component traits as surrogates for direct yield selection is especially advantageous in early-generation breeding, where large population sizes and multi-environment testing impose logistical constraints (Deshmukh *et al.*, 2018). In contrast, relative water content was negatively associated with grain yield at the phenotypic level, suggesting possible trade-offs between moisture retention and grain productivity. Among physiological traits, chlorophyll content exhibited a strong positive correlation with grain yield ($r = 0.992$) and membrane stability index was positively correlated with both relative water content ($r = 0.243$) and flag leaf area ($r = 0.068$), reflecting coordinated stress-adaptive responses. Significant positive associations between chlorophyll content and grain yield and between membrane stability index and yield under stress conditions, suggest that these parameters capture genotypic differences in stress adaptation that ultimately translate into productivity advantages (Serba *et al.*, 2020; Kholová *et al.*, 2012) in pearl millet.

This two-years, multi-location evaluation of 300 pearl millet genotypes revealed substantial genetic diversity for key morphological and physiological traits, underscored by high heritability and appreciable genetic advance indicating that these traits are governed largely by additive gene action and are amenable to direct phenotypic selection. Based on mean performance across environments, a set of promising genotypes was identified (Table 8) for further breeding use. Notably, genotypes IC-370523, IC-373431 and IC-102804 combined superior performance across multiple traits grain yield per plant, dry panicle weight and thousand-seed weight making them valuable genotypes for future selection. Grain yield per plant showed strong positive associations with dry panicle weight, post-threshing panicle weight, thousand-seed weight and chlorophyll content, confirming these as reliable indirect selection criteria for yield improvement. Overall, the convergence of high heritability, substantial

genetic advance, and consistent positive trait associations provides a robust empirical foundation for integrating morphological and physiological screening into pearl millet improvement strategies, particularly for stress-prone environments.

ACKNOWLEDGEMENT

The authors thank Agriculture University, Jodhpur, Agriculture Research Station, Bikaner and Agriculture Research Sub Station, Nagaur for the support in conducting the study.

REFERENCES

- Annual report 2022. *All India Coordinated Small Millets Improvement Project*. ICAR–Directorate of Millets Research, Hyderabad, India.
- Al-Jibouri, H.A., Miller, P.A. and Robinson, H.F. 1958. Genotypic and environmental variances and covariances in an upland cotton cross of interspecific origin. *Agronomy Journal*, **50** (10): 633–636. [\[Cross Ref\]](#)
- Allard, R.W. 1960. Relationship between genetic diversity and consistency performance in different environments. *Crop Science*, **1** (2): 127-133. [\[Cross Ref\]](#)
- Annamalai, R., Aananthi, N., Arumugam P.M. and Leninraja, D. 2020. Assessment of variability and character association in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *International Journal of Current Microbiology and Applied Sciences*, **9** (6): 3247-3259. [\[Cross Ref\]](#)
- Arnon, D.I. 1949. Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. *Plant Physiology*, **24** (1): 1–15. [\[Cross Ref\]](#)
- Arunachalam, A., Paul, S.K. and Debnath, A. 2022. Assessment of genetic variability in sorghum (*Sorghum bicolor* L.) for physiological traits under drought. *International Journal of Agriculture Sciences*, **14** (3): 102–107.

- Burton, G.W. and De Vane, E.H. 1953. Estimating heritability in tall fescue (*Festuca ruginosa*) from replicated clonal material. *Agronomy Journal*, **54**:478-481. [\[Cross Ref\]](#)
- Deshmukh, S.N., Basu, M.S. and Reddy, P.S. 2018. Genetic variability, character association and path coefficient analysis in pearl millet. *Journal of Agricultural Sciences*, **10** (1): 41–45
- Dewey, D.R. and Lu, K.H. 1959. A correlation and path analysis of components of crested wheat grass seed production. *Agronomy Journal*, **51** : 513-518. [\[Cross Ref\]](#)
- Falconer, D.S. and Mackay, T.F.C. 1996. Introduction to Quantitative Genetics, Ed 4. Longmans Green, Harlow, Essex, UK.
- Farooq, M., Wahid, A., Kobayashi, N., Fujita, D. and Basra, S.M.A. 2009. Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development*, **29** (1): 185–212. [\[Cross Ref\]](#)
- Hasan-Ud-Daula, H. and Sarker, U. 2020. Variability, heritability, character association, and path coefficient analysis in advanced breeding lines of rice (*Oryza sativa* L.). *Genetika*, **52**: 711-726. [\[Cross Ref\]](#)
- Johnson, H.W., Robinson, H.F. and Comstock, R.E. 1955. Estimates of genetic and environmental variability in soybean. *Agronomy Journal*, **47**: 314-318. [\[Cross Ref\]](#)
- Kholová, J., Nepolean, T., Hash, C.T., Supriya, A., Rajaram, V. and Senthilvel, S. 2012. Water saving traits co-map with a major terminal drought tolerance quantitative trait locus in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Molecular Breeding*, **30**: 1337–1353. [\[Cross Ref\]](#)
- Narasimhulu, R., Reddy, B.S., Satyavathi, C.T. and Ajay, B.C. 2021. Analysis of the performance, variability and nature of Pearl Millet productive traits in the rainfed environment of Andhra Pradesh. *Electronic Journal of Plant Breeding*, **12**(3):766-771. [\[Cross Ref\]](#)
- Patel, J.M., Patel, M.S., Soni, N.V., Patel, H.N. and Prajapati, N.N. 2019. Genetic architecture of morphophysiological traits over environments in pearl millet [*Pennisetum glaucum*(L.) R. Br.]. *Electronic Journal Plant Breeding*, **10**(1): 127-136. [\[Cross Ref\]](#)
- Panse, V.G. and Sukhatme, P.V. 1985. Statistical Methods for Agricultural Workers. Indian Council of Agricultural Research Publication, New Delhi, p. 87-89.
- Payne, W.A., Wendt, C.W., Hossner, L.R. and Gates, C.E. 1991. Estimating pearl millet leaf area and specific leaf area. *Agronomy Journal*, p. 1-4. [\[Cross Ref\]](#)
- Reddy, P.S., Reddy, B.V.S., Bidinger, F.R. and Ramesh, S. 2013. Genetic variability for drought tolerance in sorghum. *Indian Journal of Plant Physiology*, **18** (2): 113–117.
- Sairam, R.K. 1994. Effect of moisture stress on physiological activities of two contrasting wheat genotypes. *Indian Journal of Experimental Biology*, **32**: 594–597.
- Salgotra, A. and Chauhan, S. 2023. Assessment of Genetic and Non-Genetic Variation for Quantitative Traits of Economic Importance. *Journal of Crop Improvement*, **15** (2):120-135.
- Sathya, M., Sumathi, P., Senthil, N., Vellaikumar, S. and Joel, J. 2014. Genetic studies for yield and its component traits in RIL population of pearl millet (*Pennisetum glaucum* [L.] R. Br.). *Electronic Journal of Plant Breeding*, **5** (2): 322-326.
- Serba, D.D., Yadav, R.S., Varshney, R.K., Gupta, S.K., Mahalingam, G. and Srivastava, R.K. 2020. Genomic designing of pearl millet: a resilient crop for arid and semi-arid environments, in Genomic Designing of Climate-Smart Cereal Crops, ed C. Kole (Springer Nature), p. 221–286. [\[Cross Ref\]](#)
- Sowmiya, P., Sumathi, P. and Revathi, S. 2016. Estimates of genetic parameters and quantification of betacarotene in pearl millet [*Pennisetum glaucum* L.] segregating population. *Electronic Journal of Plant Breeding*, **7** (3): 640-648. [\[Cross Ref\]](#)
- Singh, J. and Chhabra, A.K. 2018. Genetic variability and character association in advance inbred lines of pearl millet under optimal and drought conditions. *Ekin Journal of Crop Breeding and Genetics*, **4** (2): 45-51.
- Slavík, B. 1974. *Methods of Studying Plant Water Relations*. Springer-Verlag, Berlin, Heidelberg. [\[Cross Ref\]](#)
- Varshney, R.K., Shi, C., Thudi, M., Mariac, C., Wallace, J., Qi, P. and Vigouroux, Y. 2017. Pearl millet genome sequence provides a resource to improve agronomic traits in arid environments. *Nature Biotechnology*, **35** (10): 969–976. [\[Cross Ref\]](#)
- Vetriventhan, M. and Nirmalakumari, A. 2007. Character association and path analysis in pearl millet. *Madras Agricultural Journal*, **94** (1-6) : 114-117. [\[Cross Ref\]](#)
- Yadav, O.P., Gupta, S.K., Govindara, J.M., Sharma, R., Varshney, R.K., Srivastava, R.K., Rathore, A. and Mahala, R.S. 2021. Genetic gains in pearl millet in India: insights into historic breeding strategies and future perspective. *Frontier Plant Science*, **12**:645038. [\[Cross Ref\]](#)