PLANT SCIENCE TODAY
Vol 12(sp3): 01–09
https://doi.org/10.14719/pst.9382

eISSN 2348-1900

RESEARCH ARTICLE

Multi-trait based index selection for drought stress in foxtail millet genotypes

B Umasankari[1], J Arathi[1], S Lakshmipriya[1], T Anandhan[1], V Krishnan[1], S Thirumeni[1], K Manojkumar[2], S Nadaradjan[2], S K Meena[3], N Shashidhara[4] & V Vengadessan[1*]

[1]Department of Plant Breeding and Genetics, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609 603, UT of Puducherry, India

[2]Unit of Crop Physiology, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609 603, UT of Puducherry, India

[3]Department of Agronomy, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609 603, UT of Puducherry, India

[4]Department of Plant Breeding and Genetics, University of Agricultural Sciences, Dharwad, Karnataka 580 005, India

*Correspondence email - vengadessan@gmail.com

Received: 08 May 2025; Accepted: 04 August 2025; Available online: Version 1.0: 10 October 2025

Cite this article: Umasankari B, Arathi J, Lakshmipriya S, Anandhan T, Krishnan V, Thirumeni S, Manojkumar K, Nadaradjan S, Meena SK, Shashidhara N, Vengadessan V. Multi-trait based index selection for drought stress in foxtail millet genotypes. Plant Science Today. 2025; 12(sp3):01–09. https://doi.org/10.14719/pst.9382

Abstract

Foxtail millet is recognized as the second among the small millets after finger millet. It has been documented that foxtail millet exhibits a notable degree of tolerance to drought conditions. Nonetheless, the extent of drought tolerance displayed by foxtail millet varies across different genotypes. Consequently, the selection of genotypes with superior drought tolerance is imperative for prospective breeding initiatives. Hence, the current investigation was conducted to evaluate the response of foxtail millet genotypes for drought stress based on morpho-physiological and root related traits with the aim of identifying drought-tolerant genotypes. A total of twenty-three foxtail millet genotypes were examined at the Pandit Jawaharlal Nehru College of Agriculture and Research Institute (PAJANCOA & RI) located in Karaikal during the *Kharif* season of 2024. The experimental design included RBD (Randomized Block Design) with two distinct treatments (control and drought condition), each replicated three times. A comprehensive array of morphological, physiological and root-related characteristics was recorded and analysed statistically. Apart from four traits- Canopy Temperature (CTP), Leaf Temperature (LTP), Root Length (RLT) and Root Shoot Ratio (RSR) all the remaining traits exhibited a statistically significant decline in mean performance when subjected to reproductive drought stress in comparison to optimal growth conditions. The Multi-Trait Genotype-Ideotype Distance Index (MGIDI) was employed to assess and identify the genotypes that exhibited optimal performance across twenty traits. The findings indicated that genotype GPUF 18 (G5) emerged as the highest performer across both treatment conditions, showcasing its adaptability and potential for further breeding applications. Additionally, the genotypes were evaluated utilizing nine plant abiotic stress indices, which revealed significant correlations that could facilitate the selection of tolerant genotypes under varying stress scenarios. Genotype IIMR FxM 12 (G3), characterized by a low Average Sum of Rank (ASR), was identified as a drought-tolerant foxtail millet genotype predicated on single-plant yield. This study identified drought-tolerant genotypes to develop drought-resistant foxtail millet.

Keywords: abiotic stress indices; drought stress; foxtail millet; MGIDI

Introduction

The climate changes resulting from global warming, variation in the seasonal rainfall and unpredictable weather condition remind us of the need for the development of climate-resilient crops. Crops experience abiotic stresses such as drought, salinity, submergence, extreme temperatures and metal toxicity which lead to a yield loss up to 50 %. Among the abiotic stresses, drought stress is the most significant abiotic factor affecting crop production and global food security (1). The reproductive stage of growth is more sensitive to drought than the vegetative stage, resulting in decreased flower production and poor seed set which decreases seed numbers in minor millets (2). Foxtail millet is the second most widely grown small millet after finger millet. Among the small millets, foxtail millet plays a most important role and has high micronutrient content, particularly protein, fat, carbohydrate and ash, thus playing a crucial role in the food and nutritional security of the poor (3). Foxtail millet has a higher protein level than rice and is on par with wheat, while its fat content is eight times higher than that of rice and three times more than that of wheat. Foxtail millet in India is cultivated over an area of about 0.87 lakh hectares, producing nearly 0.66 lakh tonnes, with an average productivity of 762 kg per hectare (4). Although foxtail millet is said to be reasonably drought-tolerant (5), genotype-specific tolerance levels vary. Therefore, choosing genotypes that are extremely drought-tolerant is crucial for future breeding initiatives. In order to find genotypes with improved drought tolerance that can be used in future breeding programs to create better drought-tolerant cultivars, the current study was carried out to assess how foxtail millet genotypes responded to drought stress based on morpho-physiological and root-related traits.

Materials and Methods

Twenty-three genotypes of foxtail millet were selected for this investigation, which comprised 19 advanced breeding lines and four varieties (SiA 3156, DHFt 109-3, SiA 3222, ATL1) from millet research institutions (Table 1). The experiment was conducted using a RBD with three replications under control and drought stress conditions. Each genotype was raised in three rows, with an intra-plant spacing of 15 cm and an inter-row spacing of 30 cm. Weather parameter recorded during the cropping period in PAJANCOA & RI, Karaikal is presented in Fig. 1. A range of morphological, physiological and root-related parameters were systematically recorded. The morphological parameters included Days to Fifty percent Flowering (DFF), Plant Height (PHT), Number of Productive Tillers (NPT), Days To Maturity (DTM), Panicle Length (PLT), Test Weight (TWT) and Single Plant Yield (SPY). The physiological parameters encompassed Relative Water Content (RWC), Normalized Difference Vegetation Index (NDVI), Chlorophyll Content (CCT), Canopy Temperature (CTP), Photosystem II (PS II), Leaf Temperature (LTP), Stomatal Conductance (STC), Transpiration Rate (TSR) and Photosynthesis Rate (PTR). The root-related parameters, which were also evaluated, included Root Length Trait (RLT), Root Shoot Ratio (RSR), Root Fresh Weight (RFW) and Root Dry Weight (RDW). Statistical analyses, including mean performance and MGIDI for drought intensity were conducted employing R software to scrutinize the data pertaining to the observed traits throughout the experimental trials and iPASTIC was used for calculating nine yield indices.

Table 1. Details of varieties and advanced breeding lines of foxtail millet used in this study

Sl. No	Genotype code	Pedigree
G1	CRS FxM 4	Selection from GS 510
G2	GPUF 16	CO 5 x TNSi 354-3
G3	IIMR FxM 12	Selection from IC0261438
G4	SiA 4243	Pureline selection from farmers field, Kadapa
G5	GPUF 18	TNSi 356 x TNSi 357-8
G6	TNSi 390	Advanced breeding lines
G7	TNSi394	Advanced breeding lines
G8	PPK 7	Advanced breeding lines
G9	KOPF x 2107	Advanced breeding lines
G10	KOPF x 2126	Advanced breeding lines
G11	SiA 4241	Advanced breeding lines
G12	SiA 4247	Advanced breeding lines
G13	KMF 1	Advanced breeding lines
G14	KMF 2	Advanced breeding lines
G15	IIMR FxM 14 (V905/944)	Advanced breeding lines
G16	IIMR FxM 15 (V903/962)	Advanced breeding lines
G17	IIMR FxM 16(V911/974)	Advanced breeding lines
G18	IIMR FxM 17 (V934/952)	Advanced breeding lines
G19	GPUF 19	Advanced breeding lines
G20	SiA 3156	Selection from SiA 2871
G21	DHFt 109-3	CO 5 x GPUS 30
G22	SiA 3222	SiA 3075 x SiA 326
G23	Local Check	PS 4 x Ise 198

Treatment details

Treatment I (Optimum condition)

Treatment I represented the control, in which crops were grown under optimal conditions, with timely sowing. This treatment followed the standard irrigation practices stated in the crop production guide, ensuring that the crops were adequately irrigated according to established guidelines.

Treatment II (Drought stress)

Treatment II focused on inducing drought stress with timely sowing and complete irrigation till vegetative stage. In this treatment, watering was skipped after the flowering stage and during the grain filling stage for foxtail millet and soil moisture level was measured using moisture meter.

Results and Discussion

Abiotic stresses have increased in frequency and intensity due to climate change. In recent decades, these pressures have a far greater impact on agricultural crop output. Breeders consider crop stability and yield as a significant indicator of stress tolerance in a variety of growth situations in crop development initiatives (6). Because of this, screening for a particular stress's tolerance depends on the crop's ability to perform well under both stressed and non-stressed conditions. Thus, genotypes that are stress tolerant or able to tolerate harsh environments are high yielding. This study evaluated the 23 foxtail genotypes based on morphological, physiological and root-related parameters under control and drought treatment. The outcomes of the current investigation are discussed below.

Mean performance

The mean performance of twenty traits in foxtail millet under the two treatments revealed that sixteen traits, namely NDVI, PS II, CCT, RWC, STC, PTR, TSR, DFF, NPT, PLT, PHT, RFW, RDW, DTM, TWT and SPY exhibited a significant reduction under drought stress compared to the optimal condition in reproductive stage.

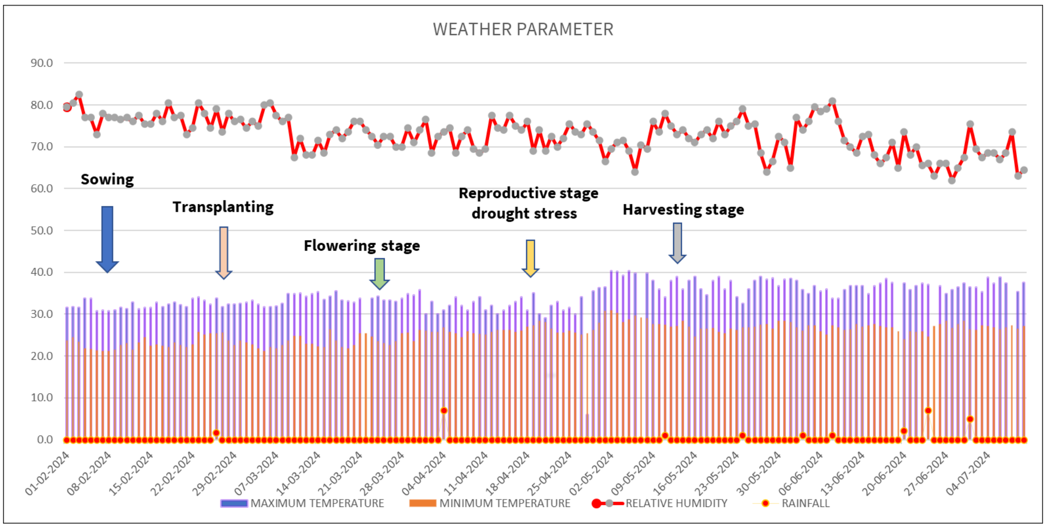

Fig. 1. Weather parameters recorded during the cropping period at PAJANCOA & RI, Karaikal.

The other four traits, CTP, LTP, RLT and RSR showed an increase in their mean values after the imposition of drought stress. Moreover, the SPY and the yield contributing traits such as NPT, TWT and PLT exhibited a decrease in their mean values under drought stress. These findings agree with the previous result, which reported on significant reduction in NPT, PLT, SPY and TWT due to drought stress in small millets (7). One of the primary effects of drought stress is a reduction in leaf water status (8). Another study also suggested that the decrease in RWC under drought stress may be linked to reduced plant vigour, as seen in many species (9). A reduction in RWC leads to loss of turgor, resulting in stomatal closure and a subsequent decline in photosynthesis.

Selection based on MGIDI index

The distance between genotypes and a specified ideotype based on the breeders' requirements (10), known as MGIDI, is a novel selection method that is unaffected by weighing (economic) coefficients (11) and multi-collinearity problems (12). The technique became a potent tool for determining whether genotypes had higher mean performance and the intended selected gains, as well as for estimating the strengths and weaknesses of selected and unselected genotypes. Plant breeding procedures can benefit greatly from the innovative and distinctive MGIDI evaluation systems (13-15). In this study, MGIDI based selection was done in 23 foxtail millet genotypes evaluated under two treatments i.e. by taking all the morphological traits, root related traits and physiological traits. All variables used in the index analysis were given both desired positive and negative direction. Dimensional reduction was conducted using exponential factorial analysis, which condensed 20 traits into several final latent variables (factors) with the highest trait loadings. Specifically, six factors were identified under optimal conditions, while seven factors were found under drought stress (Table 2, 3). The selection gain analysis using MGIDI revealed desired gains in 16 out of 20 traits, with notably high predicted gains for RFW (46.23) and RDW (42.68) (Table 4). Under drought stress, gains were observed in 16 out of 20 traits, with the highest predicted gains for RDW (42.73) and RFW (31.54) (Table 5). MGIDI was used in previous studies to describe the strengths (9, 16). A strategy for employing MGIDI to find potential genotypes with productive features was presented (13). Based on MGIDI index scores with a 20 % selection pressure, the selected genotypes under optimal conditions were G15 (1.65), G5 (2.34), G12 (2.50), G20 (2.67) and G9 (2.73) (Fig. 2). For drought stress, the selected genotypes were G4 (3.20), G5 (3.25), G7 (3.36), G16 (3.94) and G10 (4.28) (Table 6, Fig. 3). The strengths and weakness view are the percentage of variance in the MGIDI index that can be attributed to each aspect. From the most contributing factor (near the plot centre) to the least contributing component (far from the plot centre), the contribution of each factor to the MGIDI is ranked for each genotype that was chosen. Under optimal conditions, G12 and G15 showed strengths in FA1 traits (STC, PTR, TSR), while G5, G9 and G20 were weaker. For FA2 (RLT, RSR, RFW, RDW, DFF), G5, G9 and G15 excelled, whereas G12 and G20 showed weaknesses. G5, G15 and G20 were strong in FA3 (PLT, PS II, PHT, LTP, DTM), while G9 and G12 lagged. G9 and G20 performed well in FA4 (SPY, NDVI), but G5, G15 and G12 had weaker performances. G12 excelled in FA5 (TWT, CCT, CTP) and G5 in FA6 (NPT, RWC); G5, G9, G15 and G20 had weaknesses in these areas (Fig. 4). Under drought stress, G10 was strong in FA1

Table 2. Factor loadings under optimum condition for twenty traits in foxtail millet

Traits	FA1	FA2	FA3	FA4	FA5	FA6
STC	**-0.823**	-0.177	0.156	-0.167	-0.089	-0.054
PTR	**-0.832**	-0.243	0.191	-0.289	-0.065	0.036
TSR	**-0.770**	-0.149	0.302	-0.244	-0.296	0.019
RLT	-0.061	**-0.814**	0.311	-0.255	0.157	0.114
RSR	-0.030	**-0.854**	0.139	0.179	0.086	0.047
RFW	-0.307	**-0.726**	0.036	-0.108	-0.206	0.180
RDW	-0.397	**-0.802**	0.016	-0.069	0.073	0.068
DFF	-0.041	**0.464**	-0.173	0.429	0.403	0.425
PLT	-0.297	-0.122	**0.862**	0.111	0.070	0.075
PS II	-0.141	0.060	**0.741**	-0.387	-0.223	-0.091
PHT	-0.407	-0.284	**0.593**	-0.477	-0.209	0.097
LTP	-0.548	-0.152	**0.607**	0.169	0.013	-0.005
DTM	0.113	0.245	**-0.879**	0.255	0.070	0.044
SPY	-0.242	0.132	0.254	**-0.696**	-0.101	0.147
NDVI	-0.237	-0.184	0.049	**-0.849**	0.041	-0.059
TWT	-0.253	0.015	0.114	-0.048	**-0.683**	0.187
CCT	0.068	-0.182	0.448	-0.327	**0.464**	-0.106
CTP	-0.020	0.029	0.036	-0.071	**-0.860**	-0.210
NPT	-0.272	0.263	-0.270	-0.309	0.058	**-0.725**
RWC	-0.157	-0.163	-0.192	-0.293	0.038	**0.837**
EV	**6.89**	**2.59**	**1.96**	**1.60**	**1.46**	**1.26**
PV (%)	**34.45**	**12.95**	**9.78**	**7.98**	**7.31**	**6.32**
COV (%)	**34.45**	**47.40**	**57.19**	**65.17**	**72.48**	**78.79**

Table 3. Factor loadings under drought condition for twenty traits in foxtail millet

Traits	FA1	FA2	FA3	FA4	FA5	FA6	FA7
PLT	**-0.721**	-0.063	-0.110	0.277	0.070	0.145	0.275
CCT	**-0.756**	0.426	-0.011	-0.031	0.234	-0.227	-0.088
PHT	**-0.721**	-0.123	0.153	-0.216	0.134	0.463	0.092
DTM	**0.728**	0.089	-0.192	-0.157	0.075	-0.408	-0.312
TWT	-0.219	**0.839**	-0.150	0.221	0.167	0.248	0.089
SPY	-0.590	**-0.632**	0.040	0.286	-0.083	-0.175	-0.056
STC	0.029	**-0.685**	-0.071	0.391	0.066	0.287	0.350
PTR	0.025	**-0.818**	-0.016	0.169	0.174	0.139	0.149
TSR	-0.481	**-0.712**	-0.021	-0.054	0.217	0.141	0.180
PS II	-0.369	0.341	**0.415**	-0.317	0.333	0.344	-0.307
RLT	-0.137	-0.038	**0.961**	0.057	-0.037	-0.006	0.091
RSR	0.405	-0.051	**0.693**	0.024	0.077	-0.487	-0.102
NPT	-0.032	-0.019	-0.143	**-0.862**	-0.062	-0.051	0.205
RWC	-0.286	-0.219	-0.055	**0.731**	0.055	-0.216	0.174
RFW	0.022	-0.171	0.150	0.252	**0.571**	0.283	0.418
RDW	-0.129	-0.048	0.369	0.114	**0.619**	0.088	0.115
CTP	-0.076	-0.022	-0.267	-0.061	**0.850**	-0.084	-0.169
DFF	0.274	0.000	-0.373	-0.170	-0.078	**-0.437**	-0.432
LTP	-0.104	-0.066	-0.133	-0.090	0.057	**0.846**	-0.020
NDVI	-0.242	-0.191	0.015	-0.163	-0.013	-0.042	**0.846**
EV	**5.02**	**3.24**	**2.12**	**1.78**	**1.57**	**1.40**	**1.01**
PV (%)	**25.08**	**16.19**	**10.62**	**8.90**	**7.85**	**7.00**	**5.07**
COV (%)	**25.08**	**41.27**	**51.89**	**60.79**	**68.65**	**75.64**	**80.71**

Table 4. Selection gain under optimum condition for twenty traits in foxtail millet

Traits	Factor	SD %	h^2	SG %	Sense
STC	FA1	**20.17**	0.88	**17.81**	Increase
PTR	FA1	10.56	0.97	10.23	Increase
TSR	FA1	7.69	0.97	7.45	Increase
RLT	FA2	7.34	0.95	6.96	Increase
RSR	FA2	3.92	0.64	2.50	Increase
RFW	FA2	**48.84**	0.95	**46.23**	Increase
RDW	FA2	**45.60**	0.94	**42.68**	Increase
DFF	FA2	-1.65	**0.98**	-1.62	Decrease
PLT	FA3	2.83	0.81	2.29	Increase
PS II	FA3	-2.09	0.51	-1.06	Increase
PHT	FA3	3.33	**0.99**	3.31	Increase
LTP	FA3	-1.59	0.73	-1.16	Decrease
DTM	FA3	-0.02	0.97	-0.02	Decrease
SPY	FA4	11.78	**0.98**	11.58	Increase
NDVI	FA4	0.05	0.64	0.03	Increase
TWT	FA5	0.31	0.25	0.08	Increase
CCT	FA5	-0.91	0.94	-0.85	Increase
CTP	FA5	0.49	0.60	0.30	Decrease
NPT	FA6	-1.23	0.91	-1.12	Increase
RWC	FA6	13.82	0.96	13.32	Increase

Table 5. Selection gain under drought stress for twenty traits in foxtail millet

Traits	Factor	SD %	h^2	SG %	Sense
PLT	FA1	9.33	0.89	8.28	Increase
CCT	FA1	**13.25**	0.97	**12.91**	Increase
PHT	FA1	5.10	**0.99**	5.06	Increase
DTM	FA1	2.35	0.97	2.28	Decrease
TWT	FA2	0.43	0.40	0.17	Increase
SPY	FA2	3.22	0.95	3.06	Increase
STC	FA2	0.24	0.96	0.23	Increase
PTR	FA2	9.16	**0.99**	9.10	Increase
TSR	FA2	8.61	**0.98**	8.42	Increase
PS II	FA3	13.38	0.83	11.13	Increase
RLT	FA3	3.24	0.90	2.92	Increase
RSR	FA3	1.25	0.47	0.59	Increase
NPT	FA4	1.02	0.93	0.95	Increase
RWC	FA4	7.16	0.97	6.97	Increase
RFW	FA5	**38.15**	0.83	**31.54**	Increase
RDW	FA5	**49.84**	0.86	**42.73**	Increase
CTP	FA5	-1.40	0.35	-0.49	Decrease
DFF	FA6	4.05	0.94	3.81	Decrease
LTP	FA6	-0.67	0.78	-0.52	Decrease
NDVI	FA7	7.63	0.96	7.29	Increase

Table 6. MGIDI index for 23 foxtail millet genotypes under optimum condition and drought stress

Sl. No.	Genotype No.	Optimum condition	Drought stress
1	G1	5.26	5.77
2	G2	2.97	5.33
3	G3	4.80	5.61
4	G4	3.39	**3.20**
5	G5	**2.34**	**3.25**
6	G6	4.10	6.02
7	G7	3.05	**3.36**
8	G8	3.06	5.54
9	G9	**2.73**	**5.66**
10	G10	3.40	4.28
11	G11	3.30	4.86
12	G12	**2.50**	4.74
13	G13	4.24	6.50
14	G14	3.58	4.71
15	G15	**1.65**	4.87
16	G16	2.79	**3.94**
17	G17	2.88	5.55
18	G18	4.01	6.74
19	G19	4.75	6.05
20	G20	**2.67**	4.50
21	G21	4.05	5.95
22	G22	5.25	6.01
23	G23	5.39	5.40

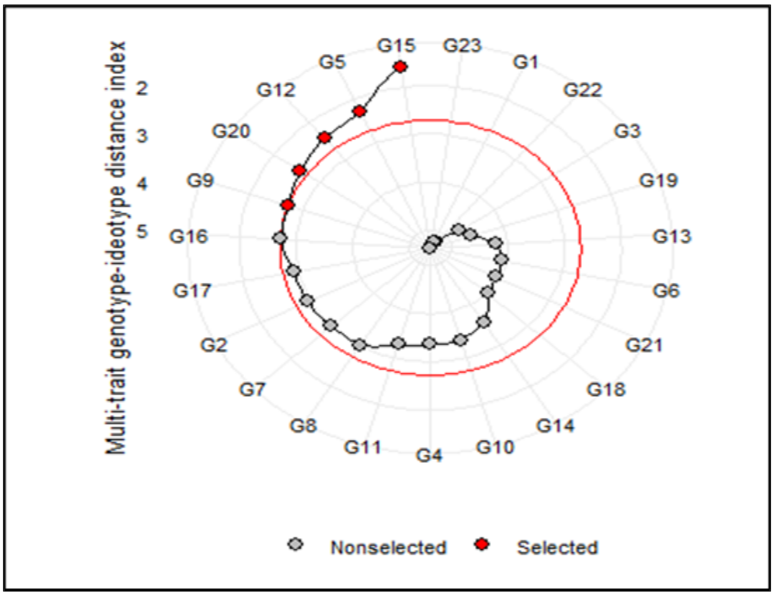

Fig. 2. Genotype ranking based on MGIDI index for 23 foxtail millet genotypes under optimum condition.

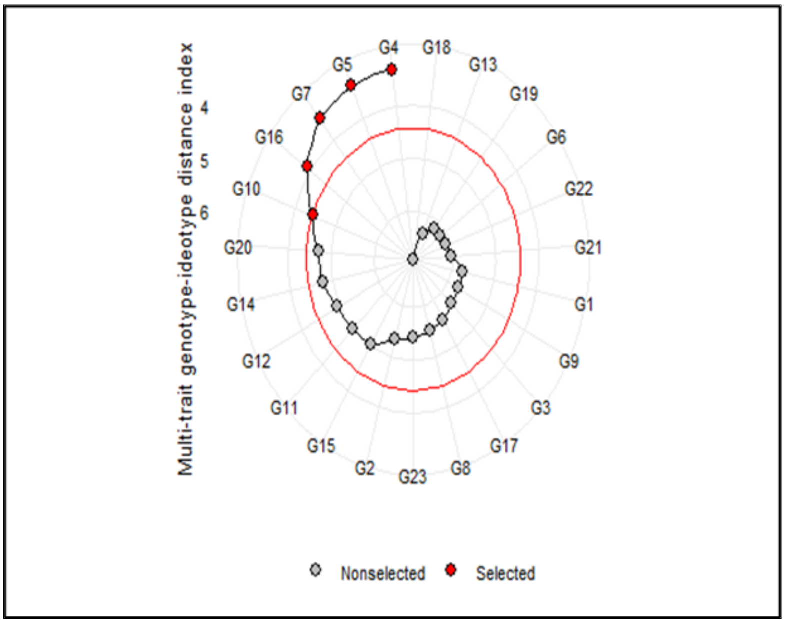

Fig. 3. Genotype ranking based on MGIDI index for 23 foxtail millet genotypes under drought stress.

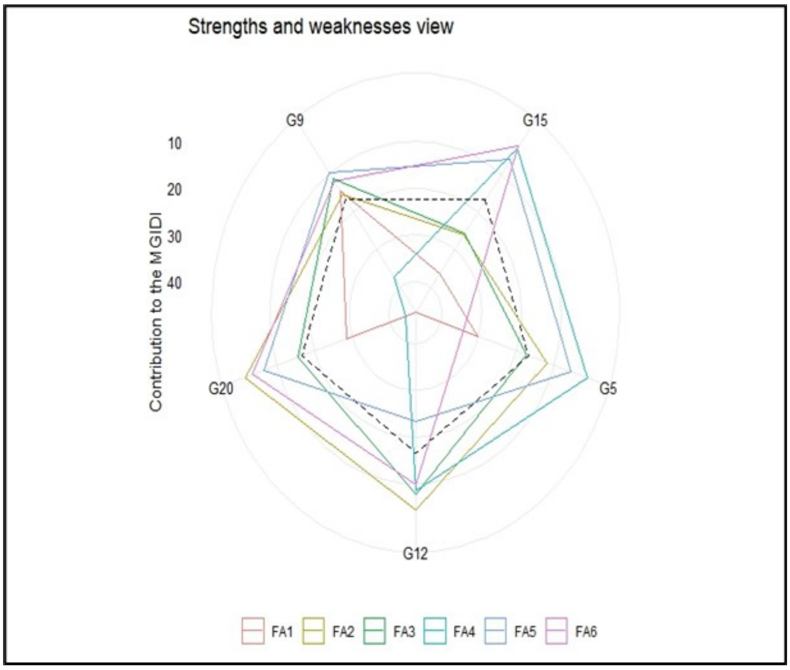

Fig. 4. Strengths and weakness view of the selected genotypes under optimum condition.

(CCT, PLT, PHT, DTM), while G4, G5, G7 and G16 showed weaknesses. G5 and G10 excelled in FA2 (STC, TWT, SPY, PTR, TSR), while G4, G7 and G16 lagged. G10 and G5 were strong in FA3 (PS II, RLT, RSR), with G4, G6 and G7 equally contributing. G16 excelled in FA4 (RWC, NPT), while G4, G5, G7 and G10 were weaker. G4 and G7 showed strengths in FA6 (DFF, LTP), but G5, G10 and G16 had weaknesses; in FA7 (NDVI), G4 and G7 excelled, while G10, G5 and G16 lagged. All genotypes showed low contributions in FA5 (RFW, RDW, LTP) (Fig. 5). Over all the genotype G5 performed well under both optimum and drought stress.

Plant abiotic stress indices based on SPY (iPASTIC)

In the control conditions, grain yield per plant (Yp) ranged from 1.87 to 31.17 g, with genotypes G5, G12, G14, G17 and G18 displaying the highest average yields. Under drought treatment, grain yield per plant (Ys) varied between 2.03 and 16.02 g with certain genotypes exhibiting the best performance (Table 7). According to the TOL index, lower values indicate greater tolerance to stress (17, 18). Based on this index, genotypes G22, G19, G9, G8 and G16 were the most stress-tolerant under drought conditions. Genotypes that exhibit tolerance will have high values for the STI, MP, GMP and HM indices when they are under stress (19). The genotypes with the highest values for these parameters under drought conditions in this study were G6, G12 and G17. An SSI (Stress Susceptibility Index) >1 denotes more vulnerability, while the SSI index finds genotypes with the least amount of yield loss under stress compared to ideal circumstances. Genotypes G5, G7, G10, G15 and G18 had high SSI values under all four treatments, while most genotypes had an SSI ≤ 1, with G1, G13, G19, G22 and G23 showing the lowest values. Three indices YI, YSI and RSI can be used to assess genotypic stability under drought stress conditions. In this study, YSI and RSI provided similar rankings for tolerant genotypes, with G8, G9, G19, G16 and G22 having the highest values under drought treatment. Relying on a single index to identify tolerant genotypes can be problematic due to varying results across different indices (19, 20). To address this, an ASR can be calculated from all indices, with lower ASR values indicating superior genotypes. In this case, G3, G4, G17, G16 and G6 were identified as the most tolerant genotypes under drought

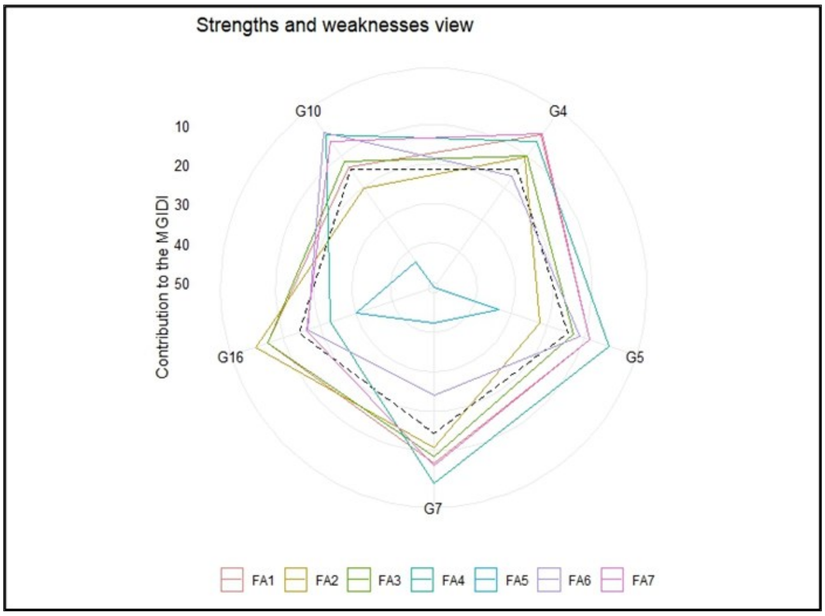

Fig. 5. Strengths and weakness view of the selected genotypes under drought stress.

Table 7. Drought stress indices for 23 foxtail millet genotypes based on SPY

Genotypes	Yp	Ys	RC	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
G1	11.23	3.11	72.31	8.12	7.17	5.91	4.87	1.19	0.09	0.39	0.28	0.70
G2	18.10	4.87	73.09	13.23	11.49	9.39	7.67	1.21	0.22	0.61	0.27	0.68
G3	15.50	10.42	32.77	5.08	12.96	12.71	12.46	0.54	0.40	1.32	0.67	1.71
G4	26.48	12.30	53.55	14.18	19.39	18.05	16.80	0.88	0.80	1.55	0.46	1.18
G5	28.93	6.98	75.87	21.95	17.96	14.21	11.25	1.25	0.50	0.88	0.24	0.61
G6	27.11	11.45	57.76	15.66	19.28	17.62	16.10	0.95	0.77	1.45	0.42	1.07
G7	22.15	4.33	80.45	17.82	13.24	9.79	7.24	1.33	0.24	0.55	0.20	0.50
G8	19.24	16.02	16.74	3.22	17.63	17.56	17.48	0.28	0.76	2.02	0.83	2.11
G9	13.01	10.73	17.52	2.28	11.87	11.82	11.76	0.29	0.34	1.35	0.82	2.09
G10	26.21	4.27	83.71	21.94	15.24	10.58	7.34	1.38	0.28	0.54	0.16	0.41
G11	27.10	10.72	60.44	16.38	18.91	17.04	15.36	1.00	0.72	1.35	0.40	1.00
G12	31.17	10.33	66.86	20.84	20.75	17.94	15.52	1.10	0.80	1.30	0.33	0.84
G13	13.14	4.66	64.54	8.48	8.90	7.83	6.88	1.06	0.15	0.59	0.35	0.90
G14	27.14	6.72	75.24	20.42	16.93	13.50	10.77	1.24	0.45	0.85	0.25	0.63
G15	19.75	3.28	83.39	16.47	11.52	8.05	5.63	1.38	0.16	0.41	0.17	0.42
G16	17.84	13.08	26.68	4.76	15.46	15.28	15.09	0.44	0.58	1.65	0.73	1.86
G17	28.70	11.77	58.99	16.93	20.24	18.38	16.69	0.97	0.83	1.49	0.41	1.04
G18	27.86	6.43	76.92	21.43	17.15	13.38	10.45	1.27	0.44	0.81	0.23	0.59
G19	6.49	5.11	21.26	1.38	5.80	5.76	5.72	0.35	0.08	0.64	0.79	2.00
G20	19.80	8.10	59.09	11.70	13.95	12.66	11.50	0.97	0.40	1.02	0.41	1.04
G21	24.27	10.84	55.34	13.43	17.56	16.22	14.99	0.91	0.65	1.37	0.45	1.13
G22	1.87	2.03	-8.56	-0.16	1.95	1.95	1.95	-0.14	0.01	0.26	1.09	2.76
G23	9.62	4.69	51.25	4.93	7.16	6.72	6.31	0.85	0.11	0.59	0.49	1.24

Yp - SPY under optimum condition

Ys - SPY under drought condition

TOL - Tolerance Index

MP - Mean Productivity

GMP - Geometric Mean Productivity

HM - Harmonic Mean

STI - Stress Tolerance Index

YI - Yield Index

YSI - Yield Stability Index

RSI - Relative Stress Index

Table 8. Ranking pattern of the 23 foxtail millet genotypes based on drought stress indices

Genotypes	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI	SR	AR	SD
G1	20	22	8	20	21	22	16	21	22	16	16	204	18.55	4.27
G2	15	16	11	18	17	15	17	17	16	17	17	176	16.00	1.90
G3	17	9	7	15	12	9	6	12	9	6	6	108	9.82	3.76
G4	8	3	13	3	2	2	8	2	3	8	8	60	**5.45**	**3.70**
G5	2	12	23	6	9	12	19	9	12	19	19	142	12.91	6.43
G6	6	5	14	4	4	4	10	4	5	10	10	76	**6.91**	**3.48**
G7	11	19	18	14	16	17	21	16	19	21	21	193	17.55	3.17
G8	14	1	4	7	5	1	2	5	1	2	2	44	**4.00**	**3.87**
G9	19	7	3	16	14	10	3	14	7	3	3	99	9.00	5.93
G10	9	20	22	12	15	16	23	15	20	23	23	198	18.00	4.88
G11	7	8	15	5	6	6	13	6	8	13	13	100	9.09	3.65
G12	1	10	20	1	3	5	15	3	10	15	15	98	8.91	6.69
G13	18	18	9	19	19	18	14	19	18	14	14	180	16.36	3.20
G14	5	13	19	10	10	13	18	10	13	18	18	147	13.36	4.48
G15	13	21	16	17	18	21	22	18	21	22	22	211	19.18	2.99
G16	16	2	5	11	8	7	5	8	2	5	5	74	**6.73**	**4.05**
G17	3	4	17	2	1	3	11	1	4	11	11	68	**6.18**	**5.36**
G18	4	14	21	9	11	14	20	11	14	20	20	158	14.36	5.46
G19	22	15	2	22	22	20	4	22	15	4	4	152	13.82	8.59
G20	12	11	10	13	13	11	12	13	11	12	12	130	11.82	0.98
G21	10	6	12	8	7	8	9	7	6	9	9	91	8.27	1.79
G22	23	23	1	23	23	23	1	23	23	1	1	165	15.00	11.10
G23	21	17	6	21	20	19	7	20	17	7	7	162	14.73	6.47

SR - Sum of rank; **AR -** Average rank; **SD -** Standard deviation

stress (Table 8).

The highly significant correlations between these indices and yield under drought treatment indicated their ability to select genotypes with high potential yield and tolerance to all two treatments (Table 9). Furthermore, the highly significant correlation between both indices suggests that they can be used interchangeably to choose tolerant genotypes. In contrast, Yp had a substantial correlation with MP, GMP, HM, STI and YI, whereas TOL, MP, GMP and STI had a strong correlation with Ys (Fig. 6). Other studies also documented this observation correspondingly in canola and chickpeas (21, 22). The first two main components with eigenvalues > 1 explained 97.40 % of the variance in yield performance and nine yield-related metrics during drought treatment, according to the principal component analysis (PCA) results based on the correlation matrix (Table 10). Except for YSI and RSI, all indices and yield (Yp and Ys) had a favourable impact on PC1 during drought treatment (Fig. 7). Therefore, selection

Table 9. Pearson correlation of nine stress indices under drought stress

Indices	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Yp	1.00										
Ys	0.43	1.00									
TOL	0.88**	-0.056	1.00								
MP	0.94**	0.71*	0.67	1.00							
GMP	0.81**	0.88**	0.44	0.96**	1.00						
HM	0.66	0.95**	0.23	0.87**	0.97**	1.00					
SSI	0.63	-0.30	0.86**	0.38	0.15	-0.05	1.00				
STI	0.76*	0.88**	0.37	0.92**	0.98**	0.97**	0.05	1.00			
YI	0.425	1.00**	-0.06	0.71*	0.87**	0.95**	-0.30	0.87**	1.00		
YSI	-0.63	0.30	-0.86	-0.38	-0.15	0.05	-1.00	-0.05	0.30	1.00	
RSI	-0.63	0.30	-0.86	-0.38	-0.15	0.05	-1.00	-0.05	0.30	1.00	1.00

*Significant at 5 % level ** Significant at 1 % level

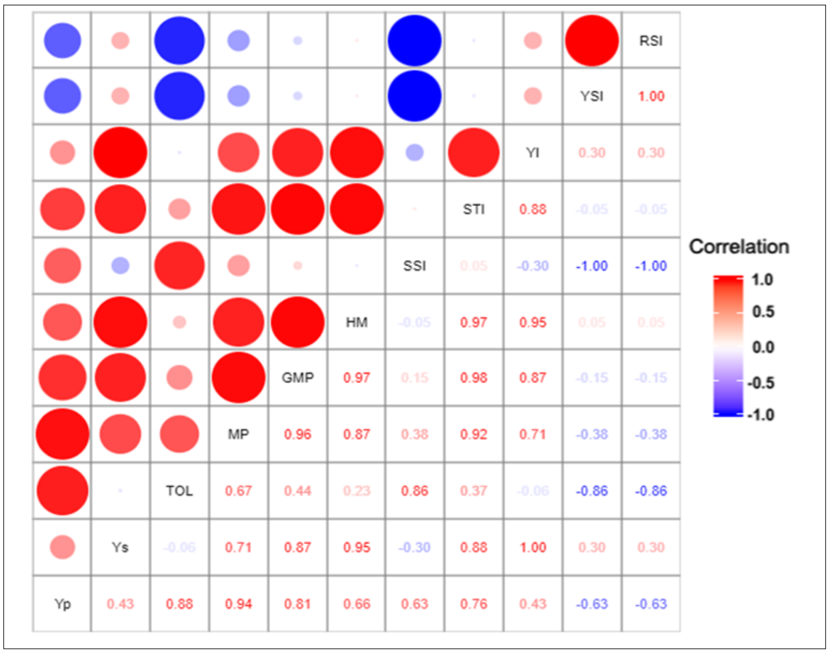

Fig. 6. Heat map depicts correlation between the stress indices under drought stress.

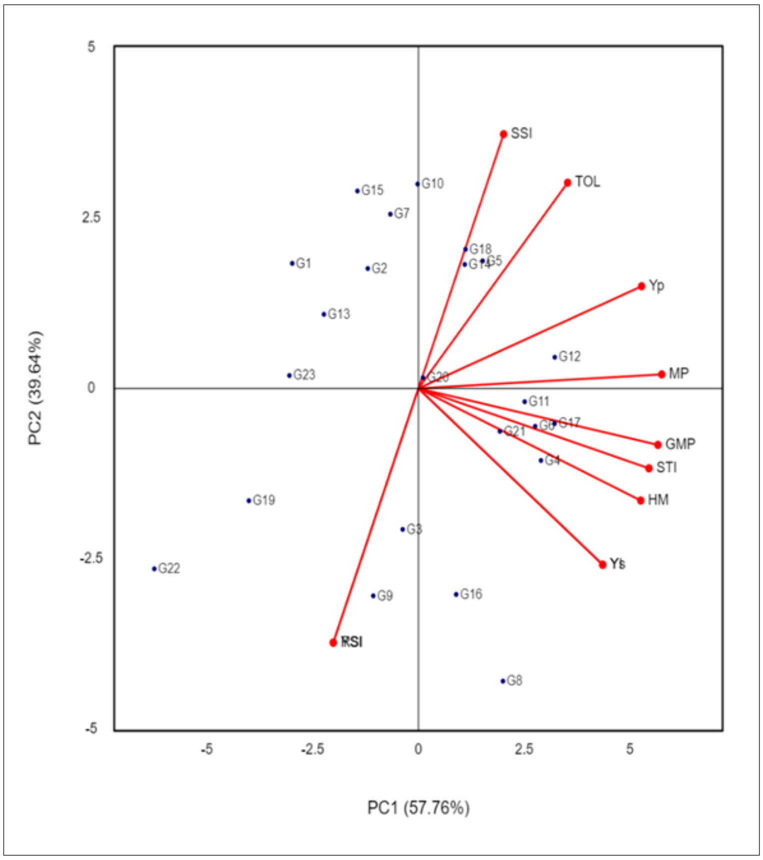

Fig. 7. Bi-plot of stress indices for 23 foxtail millet genotypes under drought stress.

Table 10. PCA for nine stress indices under drought stress in foxtail millet

Factors	PC1	PC2	PC3	PC4	PC5	PC6
Yp	**0.912**	0.371	**0.172**	**-0.046**	-0.005	**-0.0005**
Ys	0.753	**-0.640**	-0.146	**-0.052**	**-0.019**	-0.0002
TOL	0.609	**0.746**	**0.266**	-0.023	0.004	**-0.0005**
MP	**0.994**	0.051	0.080	**-0.055**	-0.011	**-0.0005**
GMP	**0.978**	-0.205	-0.007	0.005	**0.030**	**0.0042**
HM	**0.908**	-0.407	-0.080	0.036	**0.048**	**-0.0029**
SSI	0.348	**0.922**	**-0.168**	0.011	-0.003	0.00001
STI	**0.942**	-0.290	0.080	**0.148**	**-0.030**	0.00001
YI	0.753	**-0.640**	-0.146	**-0.052**	**-0.019**	-0.0002
YSI	-0.348	**-0.922**	**0.168**	-0.011	0.003	-0.00001
RSI	-0.348	**-0.922**	**0.168**	-0.011	0.003	-0.00001
EV	**6.354**	**4.360**	0.246	0.035	0.005	0.00003
POV	57.764	39.637	2.238	0.316	0.045	0.0002
CP	57.764	97.401	99.639	99.955	100.000	100.000

based on high PC1 values may aid in the identification of genotypes that are drought tolerant.

Conclusion

This study provided an outline of the genotypic response exhibited by foxtail millet in terms of their tolerance to drought conditions during reproductive growth stages. The effects of drought stress were thoroughly investigated in this study, particularly in relation to the reproductive growth stages of the crops. Based on the outcomes obtained from this initial research, the genotype GPUF 18 (G5) can be used for further study under both drought and optimum conditions. Based on the plant abiotic stress indices, the best performing genotypes were selected based on the SPY. Genotypes IIMR FxM 12 (G3) was identified as the most tolerant genotype under drought stress based on low ASR. These genotype holds immense potential for future breeding programs and genetic enhancement initiatives aimed at improving the drought tolerance of foxtail millet at reproductive stage.

Acknowledgements

All the authors acknowledge the esteemed organization PAJANCOA and RI, for the support and facilities provided for the successful conduct of the research.

Authors' contributions

BU, JA and SL conducted the experiment, recorded the data, carried out the statistical analysis and interpreted the analysis and drafted the manuscript. VV formulated the idea of the research, monitored the conduct of the experiment. VK, SKM, TA, ST, KM, SN and NS suggested corrections in the manuscript and fine-tuned the writing. 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

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used AI tools in order to rephrase the sentence. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

1. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. Plant drought stress: effects, mechanisms and management. In: Lichtfouse E, Navarrete M, Debaeke P, Véronique S, Alberola C, editors. Sustainable agriculture. Dordrecht: Springer. 2009. p.153–88. https://doi.org/10.1007/978-90-481-2666-8_12
2. Seghatoleslami MJ, Kafi M, Majidi E. Effect of drought stress at different growth stages on yield and water use efficiency of five proso millet (*Panicum miliaceum* L.) genotypes. Pak J Bot. 2008;40(4):1427–32.
3. Mal B, Padulosi S, Ravi SB, editors. Minor millets in South Asia: learnings from IFAD-NUS project in India and Nepal. Rome (Italy): Bioversity International; Chennai (India): M. S. Swaminathan Research Foundation. 2010. p. 185
4. Prabhakar PC, Ganiger BB, Bhat S, Nandini C, Kiran TV, Manjunath HA. Improved production technology for foxtail millet. Technical Bulletin. 2017;3:2017-18.
5. Lata C, Sahu PP, Prasad M. Comparative transcriptome analysis of differentially expressed genes in foxtail millet (*Setaria italica* L.) during dehydration stress. Biochem Biophys Res Commun. 2010;393(4):720–7. https://doi.org/10.1016/j.bbrc.2010.02.068
6. Chaudhry UF, Khalid MN, Aziz S, Amjad I, Khalid A, Noor H, et al. Genetic studies in different F2 segregating population for yield and fiber quality traits in cotton (*Gossypium hirsutum* L.). J Curr Opin Crop Sci. 2022;3(3):135–51. https://doi.org/10.62773/jcocs.v3i3.174
7. Ashok S, Senthil A, Sritharan N, Punitha S, Divya K, Ravikesavan R. Yield potential of small millets under drought condition. Madras Agric J. 2018;105(7–9)(2):370–2. https://doi.org/10.29321/MAJ.2018.000163
8. Farooq M, Wahid A, Lee DJ, Cheema SA, Aziz T. Drought stress: comparative time course action of the foliar applied glycinebetaine, salicylic acid, nitrous oxide, brassinosteroids and spermine in improving drought resistance of rice. J Agron Crop Sci. 2010;196(5):336–45. https://doi.org/10.1111/j.1439-037X.2010.00422.x
9. Liu Y, Fiskum G, Schubert D. Generation of reactive oxygen species by the mitochondrial electron transport chain. J Neurochem. 2002;80(5):780–7. https://doi.org/10.1046/j.0022-3042.2002.00744.x
10. Olivoto T, Nardino M, Meira D, Meier C, Follmann DN, de Souza VQ, et al. Multi-trait selection for mean performance and stability in maize. Agron J. 2021;113(5):3968–74. https://doi.org/10.1002/agj2.20741
11. Bizari EH, Val BHP, Pereira EdM, Mauro AOD, Unêda-Trevisoli SH. Selection indices for agronomic traits in segregating populations of soybean. Rev Ciênc Agron. 2017;48(1):110–7. https://doi.org/10.5935/1806-6690.20170012
12. Smith HF. A discriminant function for plant selection. Ann Eugen. 1936;7(3):240–50. https://doi.org/10.1111/j.1469-1809.1936.tb02143.x

doi.org/10.3390/agronomy11061221

14. Pour-Aboughadareh A, Sanjani S, Chaman-Abad HN, Mehrvar MR, Asadi A, Amini A. MGIDI and WAASB indices: The useful approaches for selection of salt-tolerant barley genotype at the early growth and maturity stages. Res Square. 2021. https://doi.org/10.21203/rs.3.rs-304576/v1
15. el hadj DH, Tellah S, Goumeida K, Aitouakli S, Tifest C, Ammi N, et al. Evaluation of adaptability of different faba bean landraces under Mediterranean field conditions of central-northern Algeria. Agronomy. 2022;12(7):1660. https://doi.org/10.3390/agronomy12071660
16. Gabriel A, de Resende JTV, Zeist AR, Resende LV, Resende NCV, Zeist RA. Phenotypic stability of strawberry cultivars based on physicochemical traits of fruits. Hortic Bras. 2019;37:75–81. https://doi.org/10.1590/S0102-053620190112
17. Anwaar HA, Perveen R, Mansha MZ, Abid M, Sarwar ZM, Aatif HM, et al. Assessment of grain yield indices in response to drought stress in wheat (*Triticum aestivum* L.). Saudi J Biol Sci. 2020;27(7):1818–23. https://doi.org/10.1016/j.sjbs.2019.12.009
18. Kamrani M, Hoseini Y, Ebadollahi A. Evaluation for heat stress tolerance in durum wheat genotypes using stress tolerance indices. Arch Agron Soil Sci. 2018;64(1):38–45. https://doi.org/10.1080/03650340.2017.1326104
19. Choudhary RS, Biradar DP, Katageri IS. Evaluation of sorghum RILs for moisture stress tolerance using drought tolerance indices. Pharma Innov J. 2021;10(4):39–45.
21. Khalili M, Naghavi MR, Aboughadareh AP, Talebzadeh SJ. Evaluating of drought stress tolerance based on selection indices in spring canola cultivars (*Brassica napus* L.). J Agric Sci. 2012;4(11):78–85.
22. Ganjeali A, Porsa H, Bagheri A. Assessment of Iranian chickpea (*Cicer arietinum* L.) germplasms for drought tolerance. Agric Water Manag. 2011;98(9):1477–84. https://doi.org/10.1016/j.agwat.2011.04.017

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.